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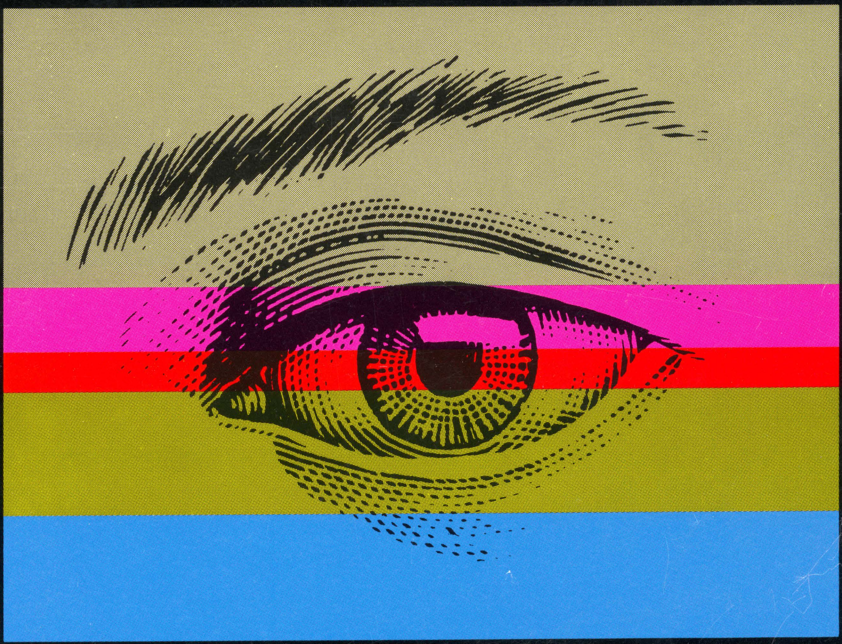

Medical Imaging, Vision, and Visual Psychophysics

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C. Carl Jaffe, M.D.*

As the radiologist interprets a medical image, a complex chain of events begins in the eye of the observer. Although knowledge of the medical image itself is paramount, it is important that the interpreter be acutely aware of the limitations of the human visual system.

In the following pages, C. Carl Jaffe, M.D. presents his position concerning the importance of knowledge of the visual process to the medical radiologist. The monograph is divided into the following sections:

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Medical Imaging Objectives

The ability to extract information from within living organisms improves the status of medicine as a scientific discipline. Yet aside from the development of the ophthalmoscope, it was not until the discovery of x-rays at the close of the nineteenth century that visual information from living internal organs could be obtained. Until that time, diagnosis was based on visible signs, abdominal palpation, and inspection of body fluids[1] (Figure 1).

The advantage of medical imaging is that it offers a representation of the body which provides spatially discrete information for interpretation. The utility of employing an image as a surrogate was recognized in earlier times though for simpler diagnostic ends (Figures 2 and 3).

Today's technology offers an abundance of imaging options. Of these, no single modality has prevailed to the exclusion of others. An essential question arises from the current diversity: *"What is it that makes an image diagnostically useful?"*

Even professionals occasionally fail to distinguish between a medical image and the anatomy one would see if the living body were opened. Ideally, the medical image serves as a record of morphology *and* physiology. Important pathology would be missed if form alone were considered the only goal and function disregarded. Properties of interest that can now be imaged are as diverse as oxygen metabolism, blood flow, metabolite consumption, and collagen matrix, as well as the usual ability to characterize the size and configuration of organs.

Medical imaging is expected to do more than simply confirm the presence or absence of disease. It must also provide for: the precise mapping of the boundaries of known disease or the staging of tumors prior to surgical removal; monitoring the response of pathologic conditions to therapy; registering the course of degenerative diseases; and providing objective information about the range of "normal" as a basis for new definitions of disease.

FIGURE 1
Tombstone of Athenian physician Jason (second century AD) illustrating early effort to assess internal abnormalities by using sense of touch (palpation). (Courtesy of British Museum, England.)

Because of biologic diversity, identical disease processes may have diverse forms and significant properties. There are, therefore, advantages in using different biologic properties for imaging the same organ if they can provide useful complementary information. Whatever the signal, all imaging methods share the common property of transforming some energy into a visual pattern in a spatially definable manner. The image may represent energy that is either transmitted through, reflected by, or emitted from structures deep in the body. However, the result represents a physical construct *that correlates with, but is not identical to, the biologic object*. The aphorism, "the map is not the territory,"[2] assumes relevance here.

In a time of rapid technologic change, it is important that all processes which influence diagnostic outcome be carefully examined to determine their influence on the whole.[3–4] Human visual psychophysics, though often taken for granted, plays a greater part in diagnostics than is usually recognized and is worth a review.[5–6]

Of all the imaging techniques, most clinicians feel the greatest familiarity with projection film radiography, since it represents a simple transillumination of the body. And yet, these film images can be mistakenly treated as all-too-familiar objects. A spirit develops that creates a greater sense of self-confidence in such visual impressions than can be justified scientifically.[7] For example, Mach band effects which occur at density boundaries are often treated psychologically as if they were physical reality.

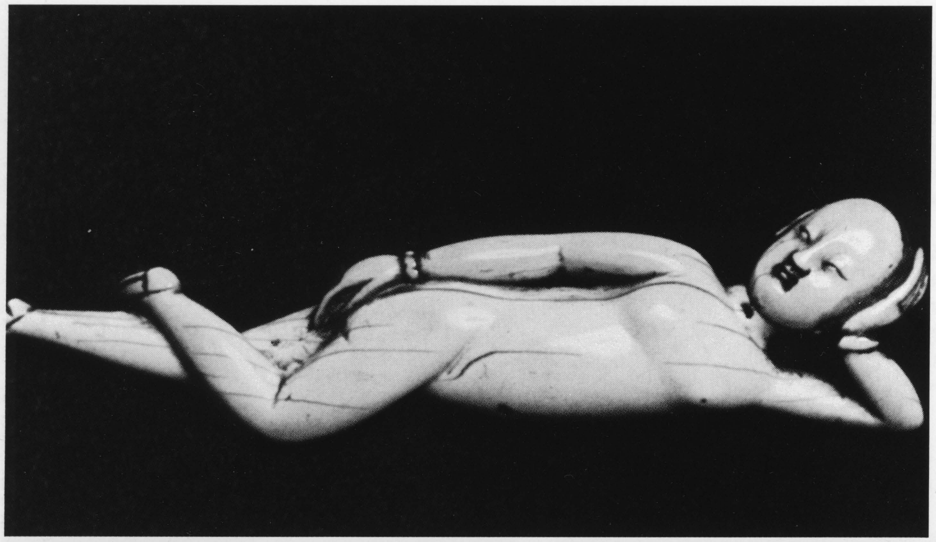


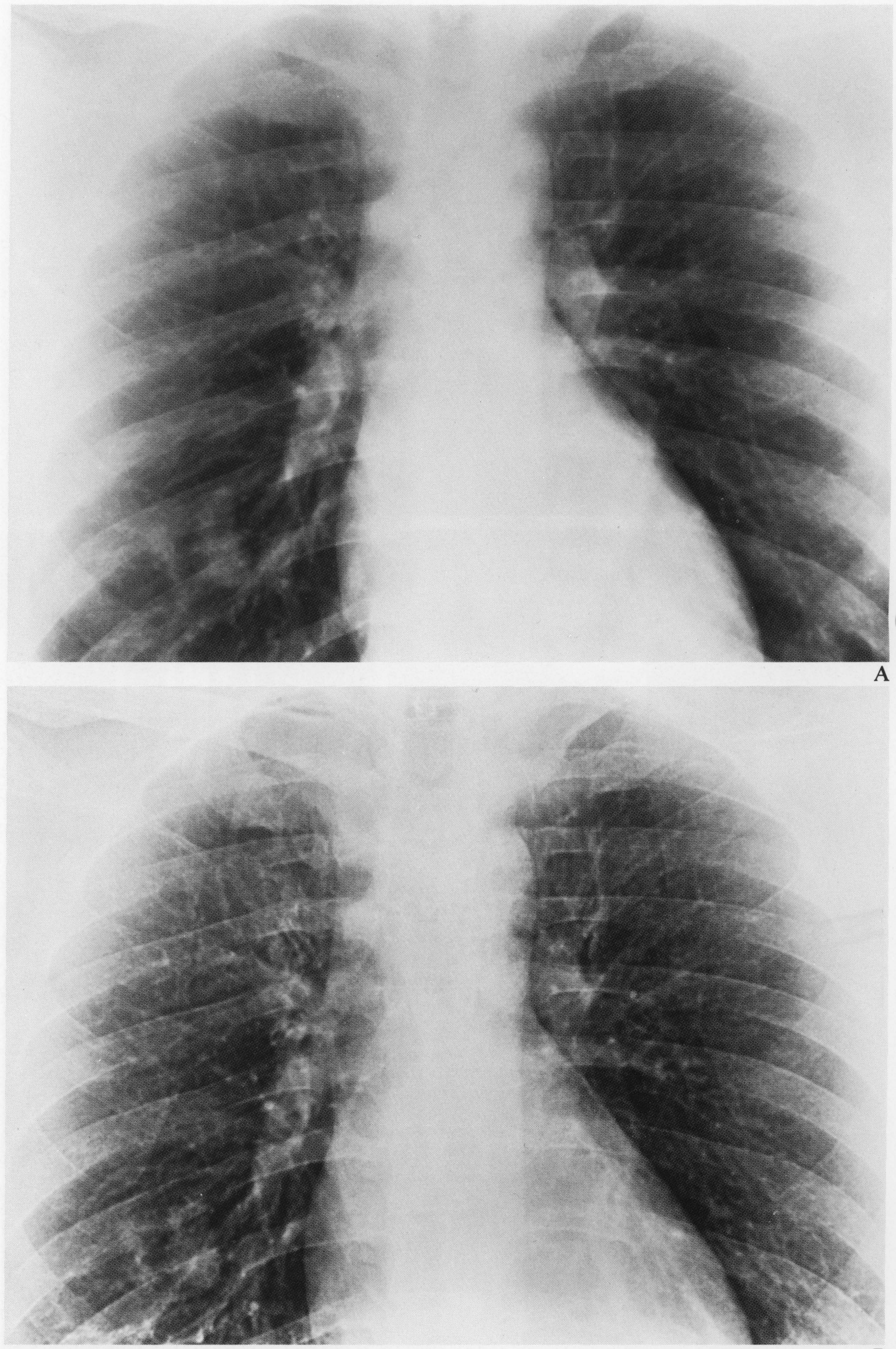
FIGURE 2
Ivory figurine used in early China as image surrogate of patient's body. The use of a surrogate permitted the patient to point discreetly to the areas of symptoms and obviate palpation by the physician.

FIGURE 3
Painting of Dr. William Clysson, by early American artist Winthrop Chandler, showing that even Western medicine recognized undesirable aspects of palpation for reasons of discretion or desire to avoid contamination. The stage was therefore set for the ready acceptance of imaging without physical contact with the patient as soon as it became technically possible.

Another issue directly originating from visual psychology is the well-established, but often forgotten, fact that both *inter*observer and *intra*observer variation in identifying subtle abnormalities in images approachs 20 to 30 percent.[8–26]

Objective evaluation of the consequences of selection of specific technical alternatives within a single imaging technique must also be considered from a psychological point of view. There is often more than one way of displaying the same signal, and it is reasonable to ask which is best for the human observer.[8] For example, in order to decide whether one mathematical approach to image smoothing in computed tomography or nuclear medicine[27] is better than another, or whether the edge enhancement present in Xeroradiographic systems produces images that are "diagnostically" equivalent to those obtained with conventional screen-film radiography, it is essential that their impact on visual psychology be examined (Figures 4 to 6).

It is customary to say that medicine is as much an art as a science. This aphorism is particularly true for radiology, in which skills, experience, and diagnostic approaches vary. It is especially apparent when discussing lesions that are visually subtle. What may be a suspicious area of density for one individual, may be dismissed as a confluence of shadows by another. Diagnosticians must become more aware of the fundamental limitations to vision and the impact of this on their use of images. Some of the most pressing questions of the art of radiology are: *What role does the image play in the diagnosis of a particular disease? Can the signal be sufficiently simplified so that it can be recognized and diagnosed equally well by all observers?*



A

B

FIGURE 4
Radiograph of same chest made with screen-film technic (A) and electroradiographic technic (B). Psychophysical questions of major magnitude occur when clinicians must evaluate the diagnostic implications of alternative display renditions of the same signal. Because an intermediary electrostatic charge was used for B, the density gradients within the image are sharper and the edges more prominent than in A. Whether this difference is diagnostically neutral or whether it implies either an impairment or an improvement will depend on training and on visual psychophysical grounds rather than on measurable physical properties.

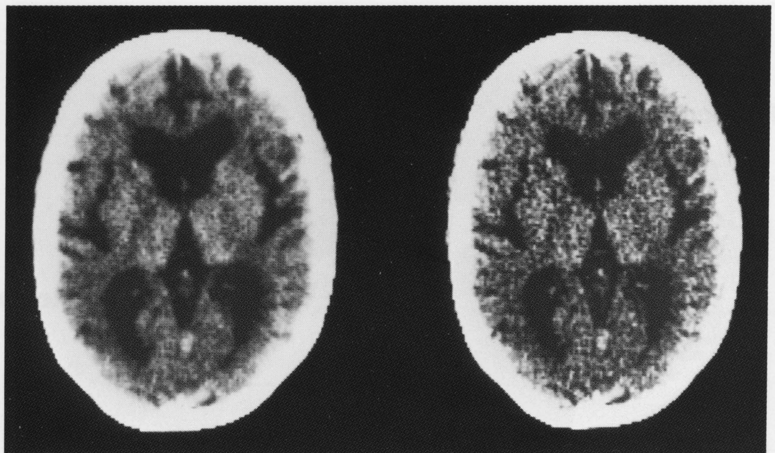
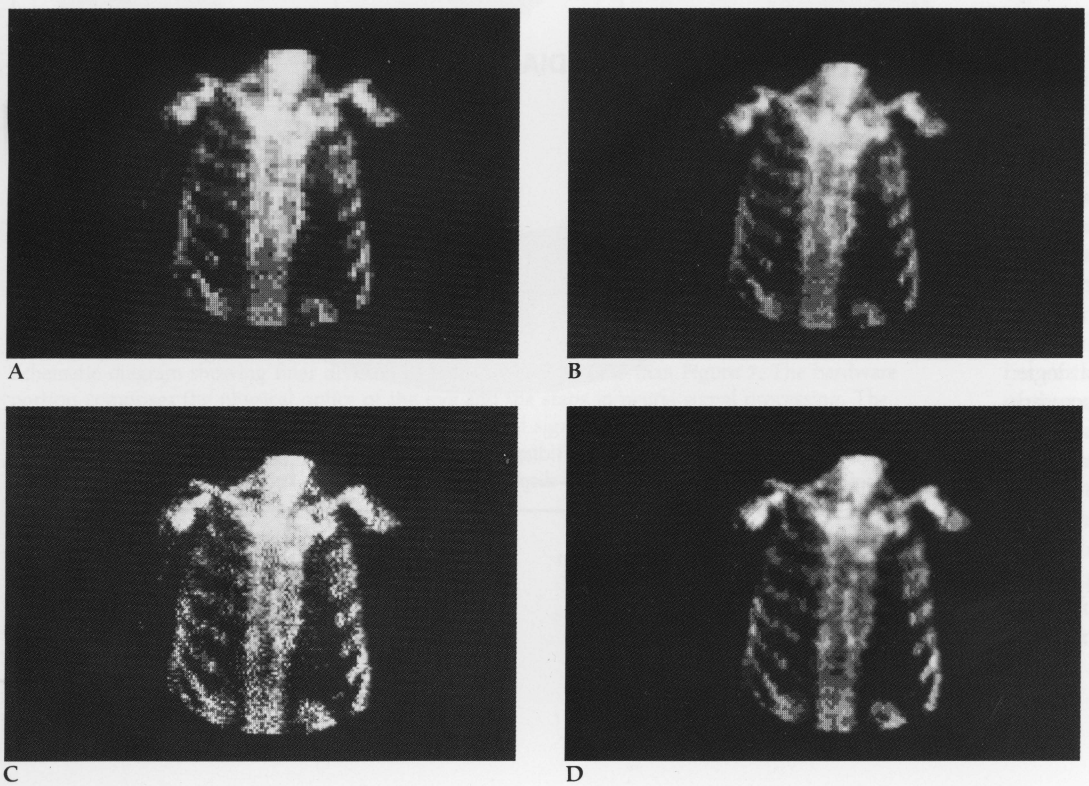


FIGURE 5
Alternative display versions of same computed tomographic (CT) scan arising from same data. The raw, unsmoothed display on the right is actually more faithful to the original data than the smooth version on the left achieved by operating on the original image using a 3 x 3 weighted mathematical filter. The smoother image is usually preferred by diagnosticians. Some CT equipment creates smooth images as a by-product of algorithms designed to suppress artifacts.



A B

C D

FIGURE 6
Same data displayed four ways. In nuclear medicine, most instruments collect data in a 64 x 64 matrix format (A) because that division properly matches the actual spatial resolution capacity of the system. The coarse appearance of individual segment blocks in A is disturbing to most observers and is most likely the result of spatial segmentation with high frequency content. The perceptibility of the image is improved simply by redisplaying the same data on a finer 128 x 128 matrix (B), which can be compared with the image created when the data is acquired in a 128 x 128 form and displayed on the same 128^2 matrix (C). The high frequency aspects of the display shown as C can be further modified by a 9-point smoothing operation (D).

The Diagnostic Process as a Cognitive Endeavor

In the past, it was generally believed that the diagnostic properties of medical images were synonymous with spatial resolution; the higher the spatial resolution, the better the quality of the diagnostic image. It is now recognized that simplification of image quality to any single parameter is problematic, since the definition of diagnostic information content is complex and can be only partially summarized.[28–33] The modulation transfer function was considered by some to be such a criterion, but it is now realized that this function is not by itself sufficient to fully characterize the usefulness and the diagnostic capacity of an imaging system. In describing and examining the possible utility of any new technic, it is important to categorize the new system with regard to the following:[34] (1) properties of the radiation interaction with tissue, (2) theoretical and practical limits of resolution, (3) dynamic range of data, (4) sources of noise (structured and unstructured), (5) artifacts, (6) image acquisition time, (7) number of images necessary for a complete examination, and (8) archival requirements. Although each new technology may provide different answers to each of these questions, such physical parameters provide information input to only single portions of the cognitive chain necessary to provide a diagnosis. Let us now examine a more complete schematic diagram of the individual steps in the diagnostic process (Figure 7).

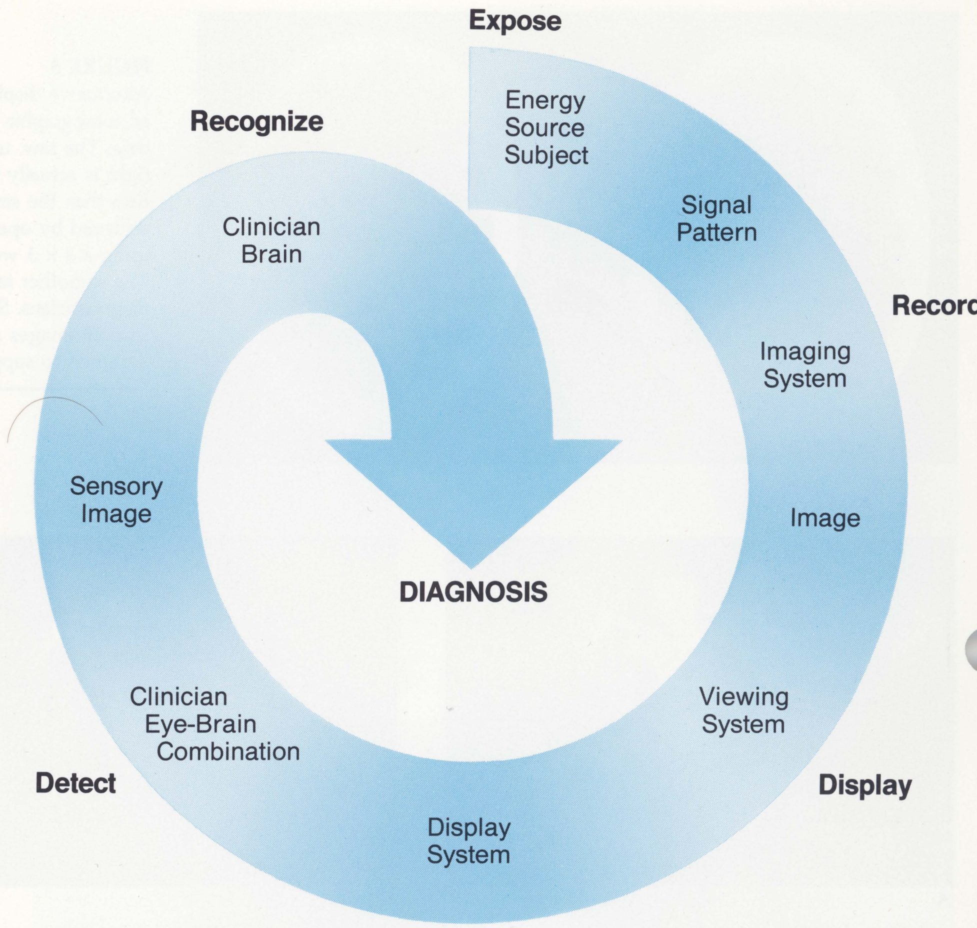


FIGURE 7
Schematic diagram of individual steps in diagnostic imaging process. Note that several visual psychophysical steps beyond the image display are required for the final diagnostic output.

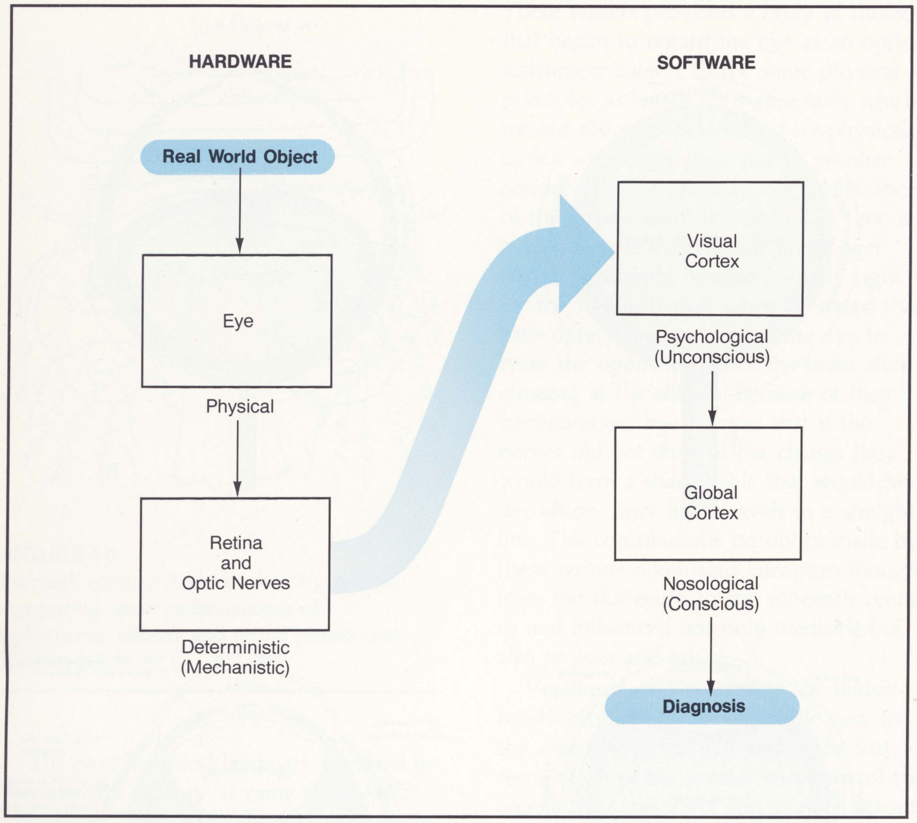


FIGURE 8
Schematic diagram showing finer division of human visual process than Figure 7. The hardware portion comprises the physical optics of the eye and the steps in neural signal processing. The software portion encompasses the more complex neural signal network of the cortex and is not so easily simplified to make possible separate testing of cognitive issues.

One can see that the final two steps depend entirely on cognitive processes residing in the human observer. Although detection and recognition are treated in the diagram as if they were independent, they cannot actually be considered fully separate entities, as will be evident later.[35–37] For the moment, however, it can be pointed out that the processes inherent in recognition that lead to a final nosology of disease can be considered to result from the training process of a medical and radiologic education, whereas the detection step can be considered as more dependent on the signal strength, or contrast, and the noise present in the image.[8] For the sake of a more detailed discussion later, it may be helpful to introduce an expanded chart of the human cognitive process (Figure 8) so that finer segments can be considered.

Using the scheme shown as Figure 8, one can consider the visual process as consisting of hardware and software elements. The software section, composed of unconscious and conscious cortical processes, is difficult to characterize predictively from its input, but the behavior of some parts of that system can be characterized. The visual hardware—that is, the physical optics of the eye and the signal conditioning of the neural tracts—has been the focus of a great deal of attention by deterministically minded neurobiologists. Contributions by these scientists in such areas as the lateral neuron inhibitor phenomenon[38] provide models for explaining and occasionally predicting overall cognitive output (including the cortex), as will be seen in a later discussion of Mach bands.[39–41]

Historical Aspects of Visual Science

Any sketch of the growth of knowledge of visual science, no matter how brief, must account for the three separate threads of anatomy, physical optics, and visual psychology.[42–45] Pre-Hippocratic anatomy identified the fluid in the eye as the principle of vision. The optic nerve was believed to be hollow (Figure 9a) in order for the visual substance to flow freely between the eye and the brain. Ptolemaic theory held that the eye emitted rays and that vision resulted from their reflection. In the Roman period, the Alexandrian anatomists fixed the seat of vision in the lens. Rufus, who was one of those scholars, gave a reasonably modern description of the eye that included both aqueous and vitreous humors but failed to recognize the posterior chamber, the greater curvature of the cornea, and the asymmetric curvature of the lens. Galen, working mainly from animal dissection, provided a description that dominated the literature until Vesalius. Galen recognized the posterior chamber, the greater curvature of the posterior surface of the lens and of the cornea, and identified the ciliary body. Galen defined vision as produced by a "pneuma," which derived from the brain, filled the space in front of the iris, dilated the pupil, and surrounded the lens. Other Romans writing about the eye included Celsus and Pliny. Even at this early date, medical therapeutic procedures described by them included surgical "couching" of a cataract by pushing the opacified substance backward and inferiorly into the globe to clarify vision.

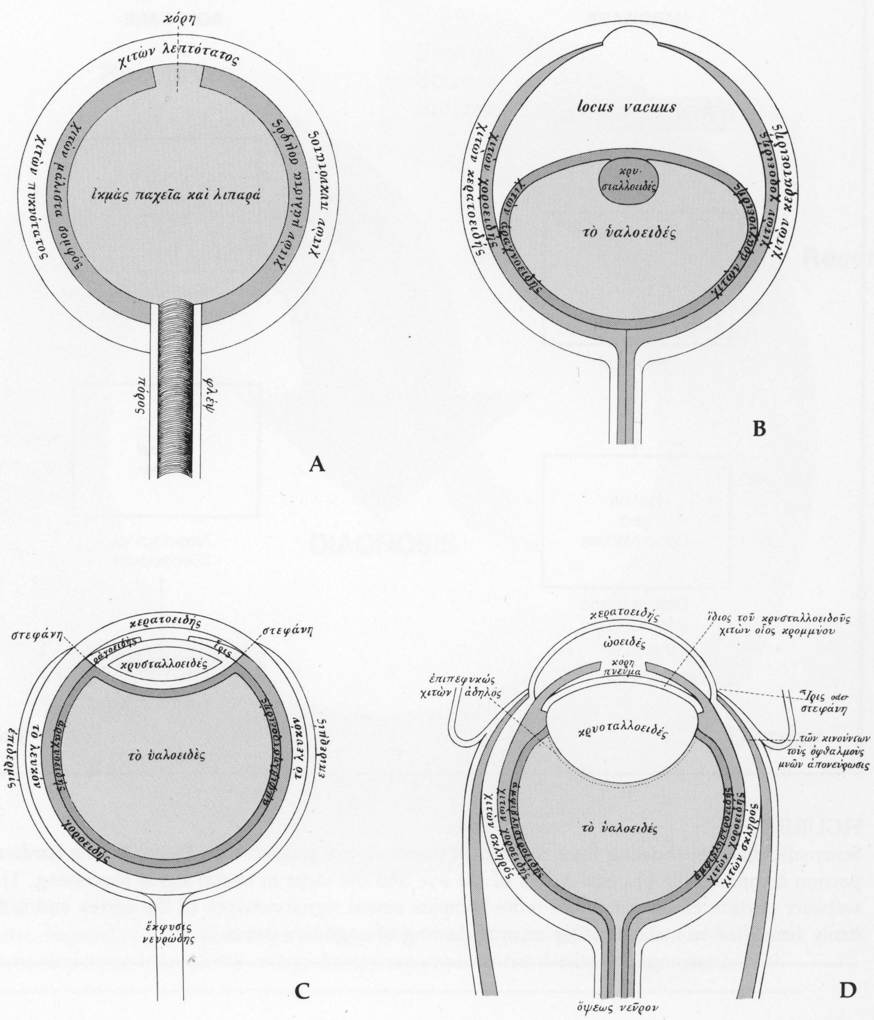


FIGURE 9
Progressive versions of anatomy of eye from pre-Hippocratic times to Galen. A: Pre-Hippocratic version (400 BC) showing optic nerve as hollow. B: Version by Celsius showing his recognition of crystalline lens, which he placed centrally in globe. C: Version by Rufus of Alexandria showing crystalline lens correctly placed forward instead of in center of globe. D: Version by Galen showing details of extraocular muscles, asymmetric curvature of lens, and greater curvature of cornea[46].

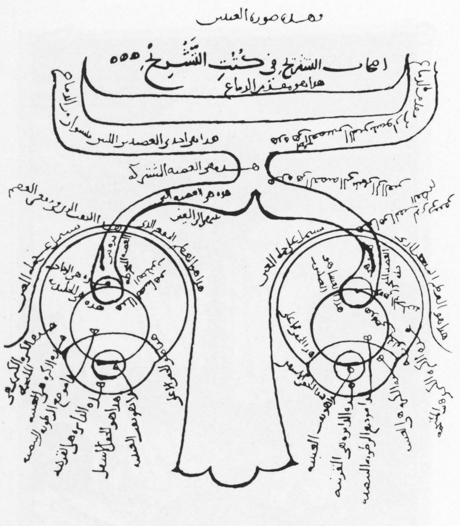


FIGURE 10
Eleventh century Arab drawing by Alhazen, suggesting some understanding of optic nerve, chiasm, and neural projections to cortex.

The next historical landmark occurred in the eleventh century. It came from Arab physicians,[47] who were the first to provide surviving drawings (Figure 10). The most important contributions were made by Alhazen, who challenged the previous conception of the eye as an emitter of rays and proposed that the eye was solely a receptor of light received from the external world. His treatises on optics used elaborate mathematical analysis to explain reflection, refraction, and perspective and were unmatched until the seventeenth century. Alhazen's work strongly influenced medieval writers (Roger Bacon,[48] John Peckham, and Witelo[49]) whose works on optics date from the thirteenth century.

These writers provided a body of thought that began to regard the eye as an optical instrument subject to the same physical principles as lenses. This approach, which treated vision as determined by physical optics, sometimes gave rise to peculiar conclusions. For example, the significance of the optic chiasm had until that time not been adequately explained, and Roger Bacon presciently became partially right for the wrong reason when he stated that each optic nerve goes from the eye to enter the opposite side of the brain after crossing at the chiasm. Because of their configuration, he reasoned that if the nerves did not cross at the chiasm they would form a sharp angle that would hinder vision, since light travels in a straight line. The contributions on optics made by these writers dominated European thought from the thirteenth to the sixteenth century and influenced not only medicine but also physics and art.

Vesalius,[50] who worked in the midsixteenth century, contributed little new to the anatomy of the eye; in fact, he lost recognition of the greater curvature of the cornea over the sclera and in error placed the lens centrally within the globe. He did, however, leave a heritage of widely circulated anatomic drawings (Figure 11).

Modern anatomy emerged only as the old concepts of the nature of vision were demolished. Fabricius (A.D. 1600) gave the true position of the lens.

Fallopius rediscovered the corneal curvature and recognized the ciliary body as a ligament binding the lens to the choroid. In 1611, Francesco Maurolycus[51] overthrew Galen's claim of the lens as the receptor of vision, and Felix Plater declared that images are formed by the lens but received on the retina. Being first in practi-

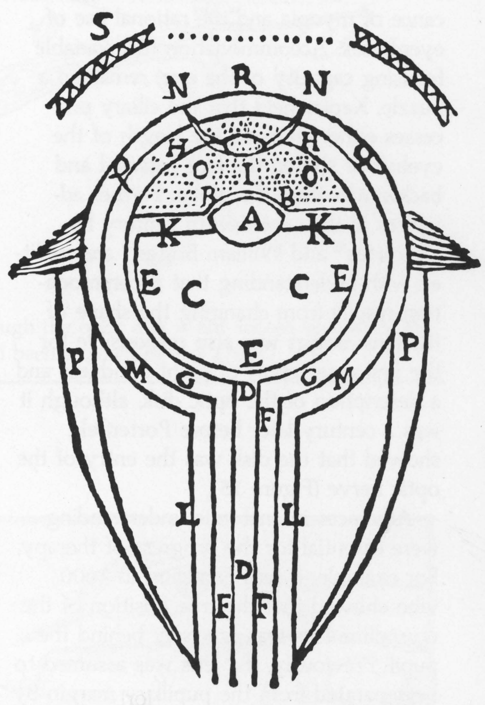


FIGURE 11
Cross section of eye by Vesalius as shown by Maurolycus.[51] Note the erroneous central placement of the crystalline lens.

cally everything, Leonardo da Vinci recognized that the eye would function in principle like the camera obscura[52] (Figure 12). Johannes Kepler[53–54] and the Jesuit Father Scheiner[55] provided full recognition of the concept of camera obscura by demonstrating that an animal eye stripped of its posterior coatings produced an inverted image on the retina, with the cornea and the lens acting as the refractive media (Figures 13 & 14). It was this understanding of the optical properties of the eye that led to an appreciation of the significance of myopia and the rational use of eyeglasses. Accommodation (the variable focusing capacity of the eye) remained a puzzle. Kepler held that the ciliary processes either changed the length of the eyeball or shifted the lens forward and backward within the globe. Further advances in the seventeenth century by Descartes[56] and William Briggs[57] are credited with understanding that accommodation results from changing the shape of the lens. Briggs was also responsible for the first case report of night blindness and a description of the optic disk, although it was a century later before Porterfield showed that the disk was the entry of the optic nerve (Figure 15).

Advances in anatomic understanding were essential for the progress of therapy. For example, it was Fabricius, in 1600, who showed that the true position of the crystalline lens was precisely behind the pupil. Previously, the lens was assumed to be separated from the pupillary margin by a fluid-filled space whose nature could become corrupted, veiling vision; hence, the term "cataract." It was on that error that the treatment known as couching was based. In 1705, Brisseau of France recognized the fact that a cataract occurred within the lens itself, although the modern method of complete extraction of a cataract via the anterior chamber was devised by Daviel, another ophthalmologic surgeon, in 1745 (Figure 16).

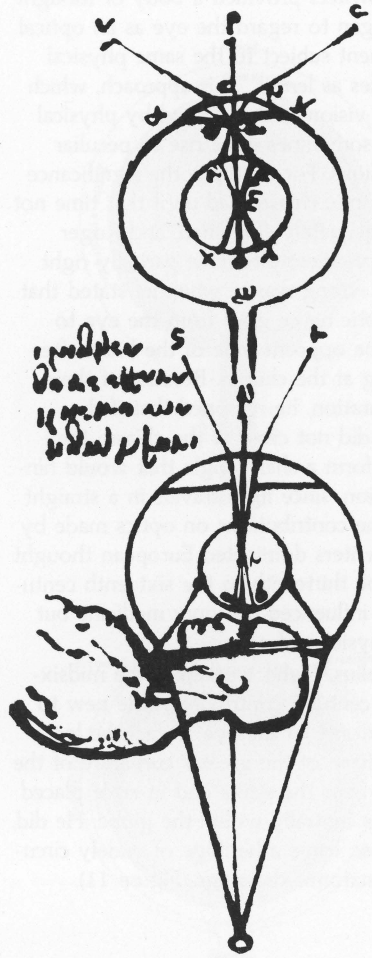
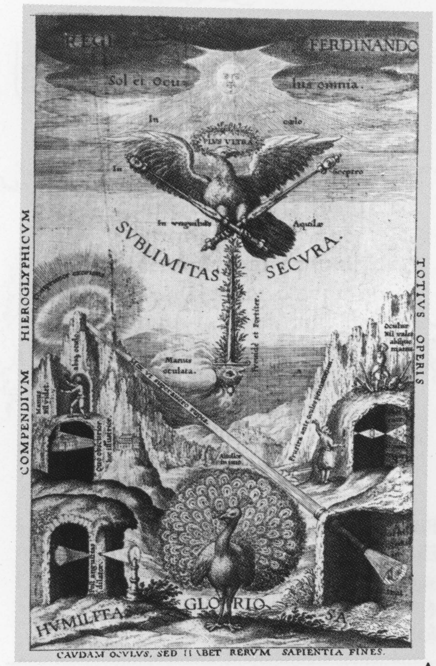
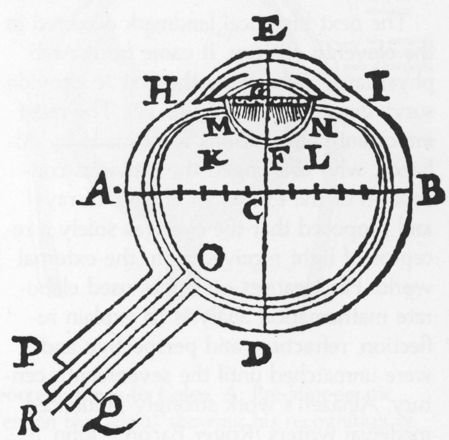


FIGURE 12
Sketch by Leonardo Da Vinci[52] indicating awareness of eye's operating as camera obscura.



A



B

FIGURE 13
Frontispiece (A) and illustration (B) from Scheiner[55] of anatomy of eye showing correct position of lens behind iris and recognition that eye functioning as camera obscura inverts image of outside world onto retina.

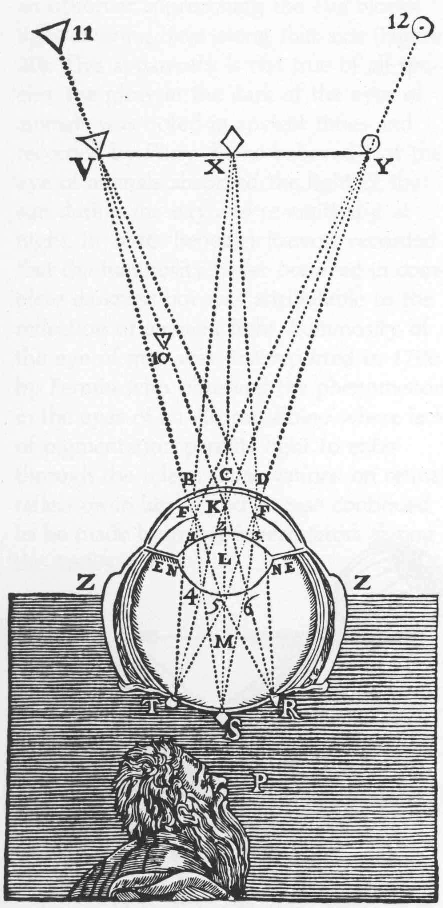


FIGURE 14
Drawing by Descartes demonstrating that retinal image is inverted form of external visual field. Following the lead of Kepler, Descartes copied an earlier experiment of stripping the back of an animal's eye to make the retina translucent.

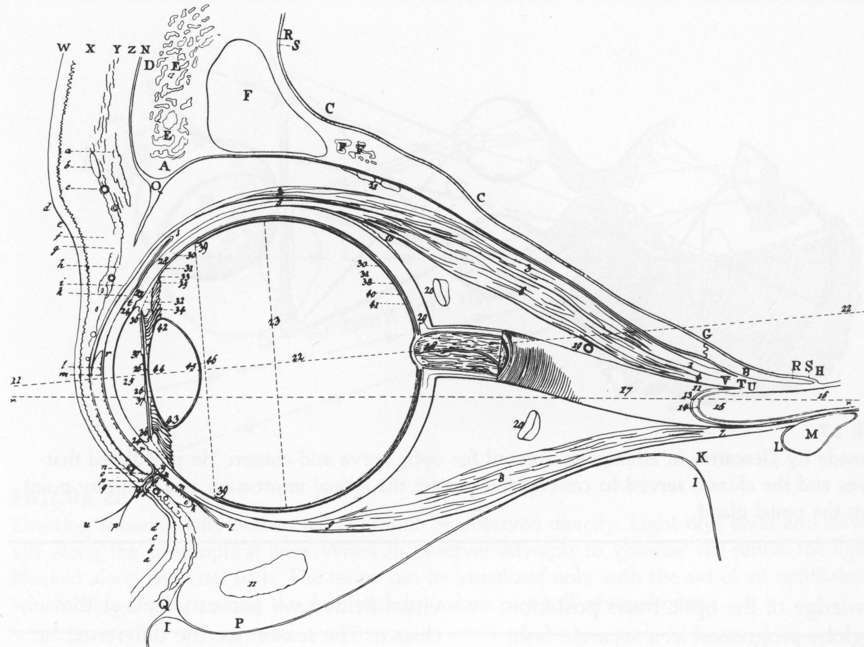


FIGURE 15
Anatomic drawing of eye made in the 1700s. Although the optic disk is not shown accurately, the drawing demonstrates the mastery of detail that had been attained by the 1700s.

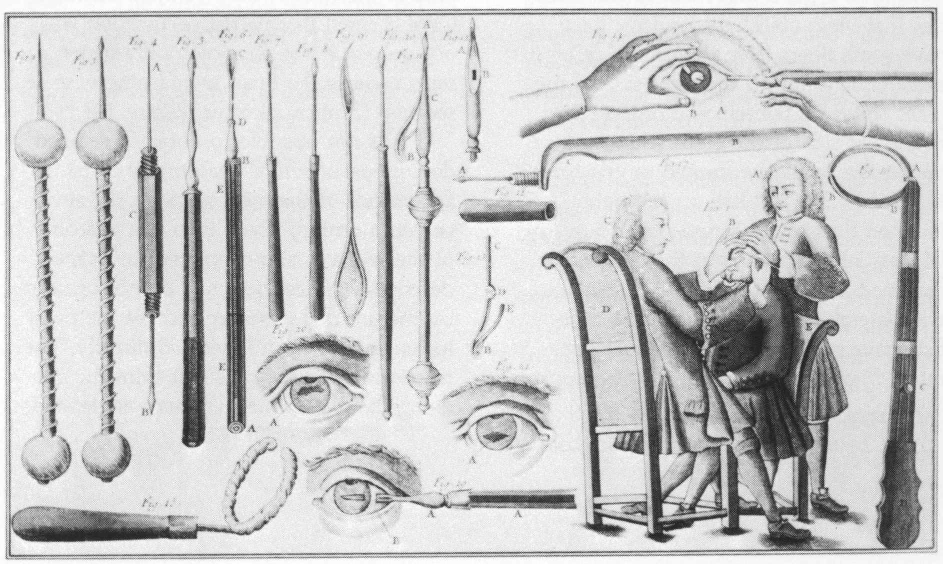


FIGURE 16
Removal of the lens through the anterior chamber as a treatment for cataracts by the 1700s replaced the earlier methods of 'couching' or pushing it back into the globe only when it was anatomically recognized that the lens itself was at fault rather than some 'corrupted humor' anterior to it.[58]

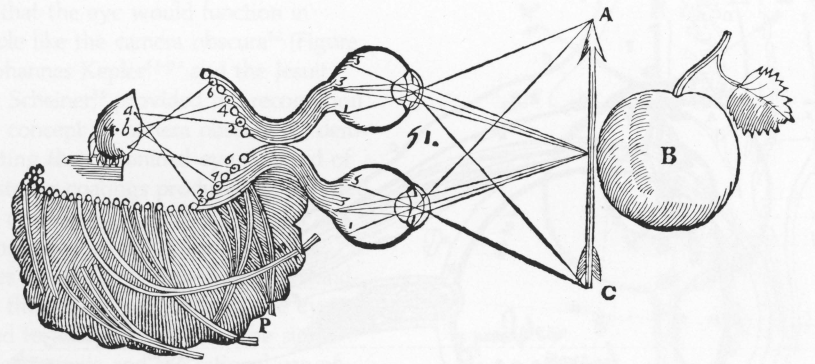


FIGURE 17
Model made by Descartes in attempt to account for optic nerve and chiasm. He postulated that the nerves and the chiasm served to convey and project the retinal impression as a point-by-point image on the pinial gland.

Knowledge of the optic tracts posterior to the globe progressed in a separate fashion. Although Descartes recognized that retinal images were inverted, he believed each optic nerve reinverted the image and unified it by point-to-point projection onto the pineal gland (Figures 17 & 18). In his model, each eye was connected by nerves to the ipsilateral side of the brain. It was Newton, in 1704, on the other hand, who argued that those animal species that view objects binocularly must have some fibers from the right side of each retina going to the right side of the brain and from the left side of the retina to the left side of the brain. Thus, only one image would be formed on the brain, half on the left and half on the right. Newton thus found it necessary to postulate partial decussation at the chiasm. He reasoned this by observing that animals with lateral, nonbinocular eyes, such as fish, have optic nerves that remain separate,[59–60] whereas animals with overlapping visual fields have nerves joined at the chiasm. The reason for the difference, he asserted, must be superimposition of the overlapping parts of the external visual fields as centrally projected to eliminate doubling of the internal image. It is interesting to note that partial decussation of human optic fibers, which Newton postulated on philosophic grounds, was finally proved anatomically by Ramon y Cajal only at the turn of the twentieth century. Cajal claimed that partial decussation was not only true but physiologically necessary, because the brain would otherwise see two identical pictures (Figure 19).

It was not possible to obtain a detailed description of retinal anatomy prior to the appearance of the microscope in the seventeenth century. Even then, the anatomy of the retina in situ continued to escape description, since the retina cannot be seen by the unaided observer because the pupil looks black when it is viewed directly. The reason is that light rays exit from the eye along the line of their entrance angle, and

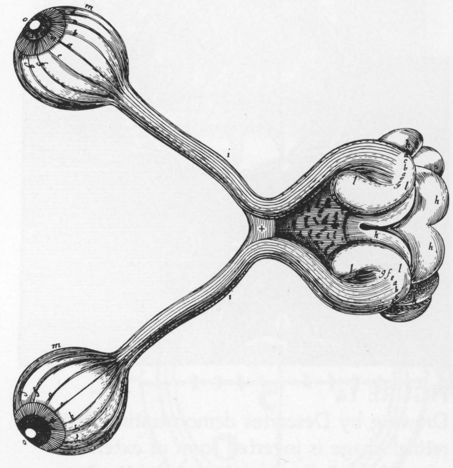


FIGURE 18
Complete separation of the projections of the optic nerves was a belief shared by both Descartes and the seventeenth century British ophthalmologist, William Briggs,[57] despite the fact that Briggs made many important original contributions.

an observer approaching the eye blocks light entering from along that axis (Figure 20). This apparently is not true of all species; the glow in the dark of the eyes of animals was noted in ancient times and recorded by Pliny. Some believed that the eye of animals absorbed the light of the sun during the day and re-emitted it at night. In 1810, Benedict Prevost recorded that the luminosity never occurred in complete darkness but was attributable to the reflection of incident light. Luminosity of the eye of man was first reported in 1796 by Fermin who observed the phenomenon in the eyes of an African albino where lack of pigmentation permits light to enter through the sclera. Observations on retinal reflection in health and disease continued to be made by many investigators during the 1800s.

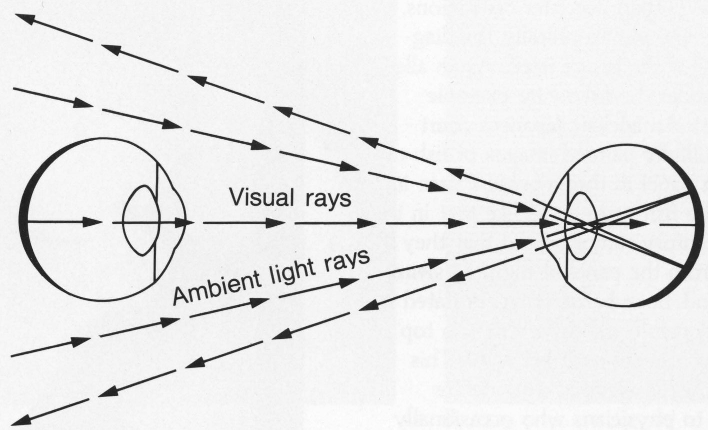


FIGURE 20
Drawing showing why human retina cannot be observed directly. Light rays enter and leave the eye along the same optical lines. When an observer attempts to visualize the retina, the light is blocked along the axial path. The retina can be visualized only with the aid of an ophthalmoscope, which brings light in along the axial path by means of a half-silvered mirror.

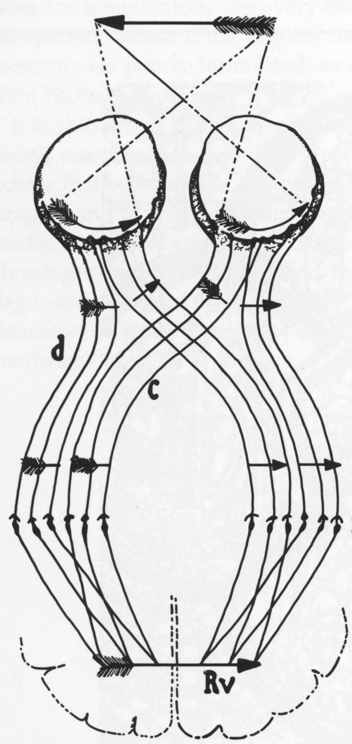


FIGURE 19
Partial decussation of the optic nerves at the chiasm with its presumed implications for single cortical image representation proven anatomically by Ramon y Cajal only at the turn of the twentieth century.

A crude ophthalmoscope was devised by the English mathematician Charles Babbage but he failed to pursue it. Hermann von Helmholtz is usually given credit for the invention in which a silvered prism is used to bring the light into the retina along the same line as the viewer's eye.[61–63] The same action sometimes occurs inadvertently when a flash unit is located too close to the axis of the camera lens during photography; the eyes of the subject photographed are pink.

With the exception of a more detailed morphologic study of the retina by light and electron microscopy, most advances in recent years have been made by electrophysiologic recording of individual retinal cells.[64] Elucidation of the lateral interaction of retinal neurons provides a framework for understanding the net effect of the inhibitory and excitatory neural processes that contribute to sharpening the edge boundaries in an image and also provides a physiologic explanation for the observed phenomena of Mach bands. Recent work has provided a clearer explanation of the cognitive response to the stimuli of both contrast and spatial frequency stimuli.[65–71] It is clear from this recent work that human vision has a peak contrast sensitivity over a fairly narrow band of low spatial frequencies. Before proceeding with a discussion of the physical properties of the eye, the diagnostic objectives desirable in a medical image will be considered.

The Image as Object

In order to prepare for later discussions, let us examine philosophically the diagnostic role of the image itself. As an allegory, consider the following example (Figure 21): An ancient Japanese court painter skillfully painted images of fish on a wooden panel in the Imperial Palace in Kyoto. The fish were so lifelike that in the ensuing century rumor spread that they escaped from the panel at night to swim in the pond. Such behavior necessitated a later court painter to draw a net on top of the fish to prevent such behavior. This example should serve as a figurative reminder to physicians who occasionally treat images as though they had a life and a reality of their own, independent of us, the observer.[72]

This confusion becomes particularly acute when one attempts to reconcile contradictory information from independent sources, a predicament not unlike a Pirandello play.[73] It should be helpful to keep in mind that medical images, no matter how faithful to human anatomy, are not the body itself but merely a representation of it. This view can lead to a greater understanding of differences between visual sensory information gathered directly from body organs and that gathered indirectly from their representation in medical images. One might then be receptive to the thought that it is the symbolic content of a medical image and not its detailed fidelity that provides information (Figure 22). Cartoons are completely premised on this fact.

Recognition that the information in a medical image is derived from a symbolic concept leads to easier acceptance of the utility of functional and more simplified imaging. As an example, one might consider the information conveyed by a left ventricular angiogram compared with that provided by a study of the heart by nuclear medicine. From the standpoint of visualizing the cardiac chamber, the spatial resolution of radiography far exceeds that of the nuclear study. From the standpoint of information content, however, volume and functional activity are considerably better conveyed by the visually simpler nuclear image (Figure 23a-b).

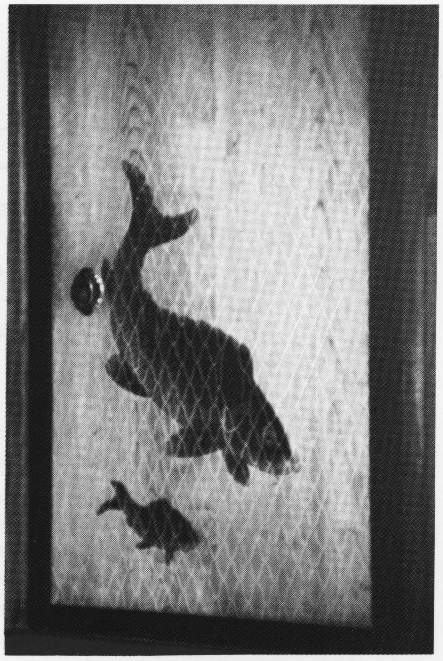


FIGURE 21
Allegorical illustration of fallacy of believing image possesses objective reality of its own (see text).

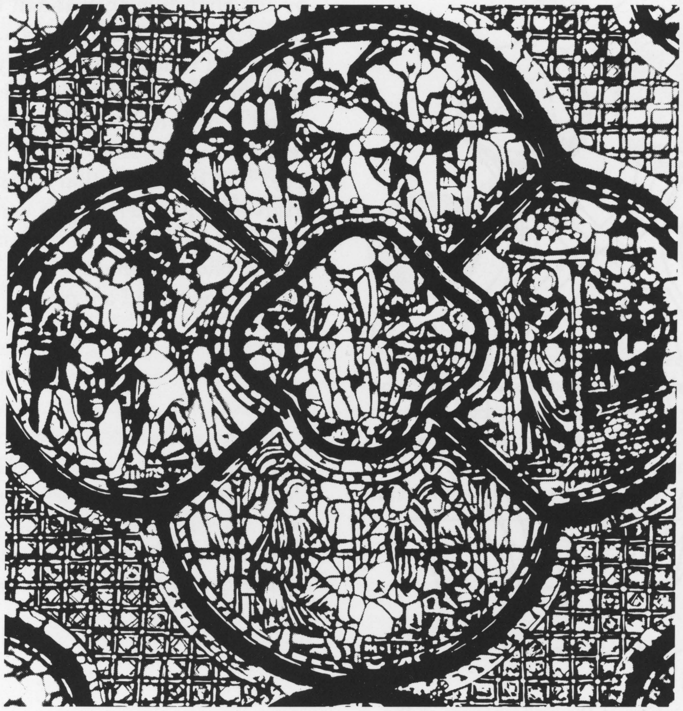
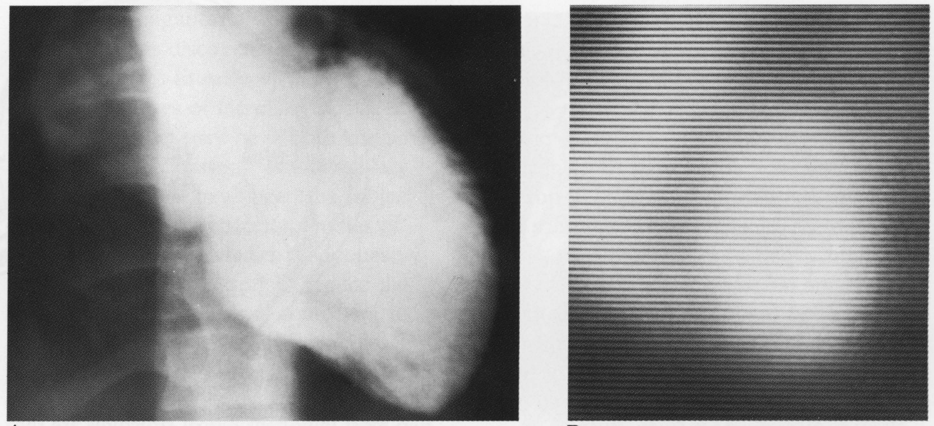


FIGURE 22
Rose window in cathedral in Chartres, France, depicting story of good Samaritan. Useful images are enriched by a cognitive content that exceeds the actual detail present in the image itself. Although all viewers can identify people and objects depicted, the full significance of this scene is accessible only to observers who share the intellectual and cultural background that increases the meaning of the scene.

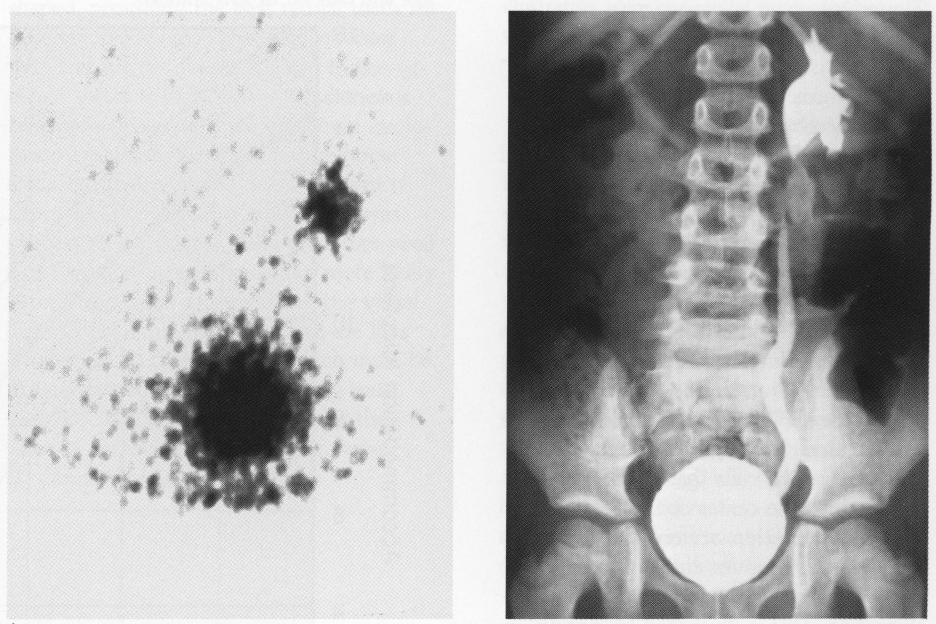
Other practical examples of this principle abound in radiography. The extent to which extraneous information is allowed or desired in a medical image is often defined by how closely the physician is able to limit the medical question. Take, for example, the imaging alternatives for evaluating vesicoureteral reflux (Figure 24a-b). From the standpoint of gathering information specifically limited to the presence or the absence of vesicoureteral reflux, both imaging technics would likely be comparably sensitive and specific. The nuclear technic, although less rich in detail, requires lower radiation dose. Moreover, it could be argued that the radiographic technic provides an image that is unnecessarily cluttered by extraneous detail of no diagnostic value. In rebuttal, a counterargument would hold that the richer details of the radiographic image permit opportunities for serendipitous discovery of unexpected disease if the original medical question was poorly formulated, as so often happens clinically.

It is thus clear that although we are always searching for a medical imaging technic that will provide a simplified, less complex and at the same time more specific image, we must also consider the advantages of imaging overkill in the diagnostic process. Let us now turn to a discussion of the physical properties, or "hardware" aspects, of the eye.



A B

FIGURE 23
Ventricular angiogram (A) and nuclear image (B). The information adequacy of two separate approaches to medical imaging of the same organ cannot be judged on the basis of physical parameters alone. The spatial resolution of the angiogram (A) exceeds that of the nuclear image (B), and yet the nuclear image could be considered to be more useful for evaluating the function of the myocardium.



A B

FIGURE 24
Nuclear image (A) and radiograph (B) made to confirm vesicoureteral reflux. Whether the higher detail of the radiograph possesses any important advantage over the cognitively simpler nuclear image depends on how willing clinicians are to confine the diagnostic question to a very specific entity.

Physical Aspects of The Eye

Although the gross structure of the eye is well known, there are a number of lesser known facts that merit brief mention for later reference (Figure 25).

It is often thought that the lens is primarily responsible for bending the light that forms the retinal image. This is not entirely true. The power of a substance to bend light depends on the difference between the refractive index of the substance and the media surrounding it. Because the cornea is adjacent to air, its refractive index is greater than that of the lens,[58] and most of the bending, therefore, is done by the front surface of the cornea. If the lens were absent and the cornea intact, parallel light rays would converge at a point only 1 cm behind the retina. Moreover, because the retina is cup-shaped, it is actually possible for a person to see 14 degrees posterior to the plane of the lens, thus lending credence to the claim that one can see behind one's back[74] (Figure 26).

By changing its shape, the normal lens is capable of accommodation to permit variable focus. At rest, the eye is focused for distant objects (this varies with the species—in fish, the resting eye is focused for near objects and accommodation is achieved by moving the whole lens rather than changing its spherical shape). When an object is 0.2 metres away, the human lens will accommodate by 5 diopters (a diopter is the reciprocal of the focal length of the lens in metres). The normal young adult has 10 diopters of accommodation, but this flexibility is lost as the cells of the lens become more rigid with age (Figure 27). Because the cells that are formed in the lens die, the center of the lens, which is its oldest portion, stiffens and yellows with age.[75] Moreover, the lens is imperfectly formed and is subject to chromatic aberration. This is illustrated by noting that when viewed, the sun has a colored fringe.[76] The practical effect of this is that objects that are viewed monochromatically (as when one wears yellow sunglasses) tend to look sharper because they lack fringes of color.

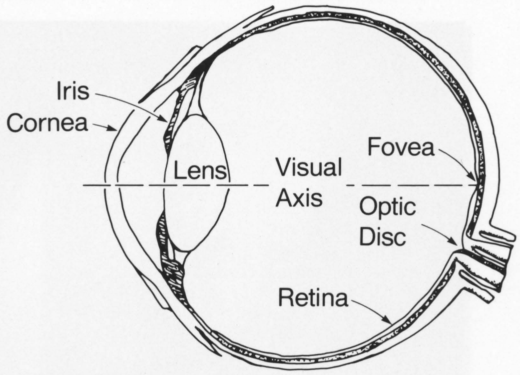


FIGURE 25
Drawing showing visual axis of eye. The two most important retinal structures are the fovea and the optic disk. Note that the optic nerve exits at the disk nasal to the fovea but that this represents the temporal portion of the field.

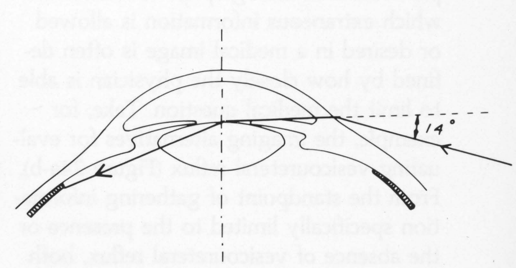
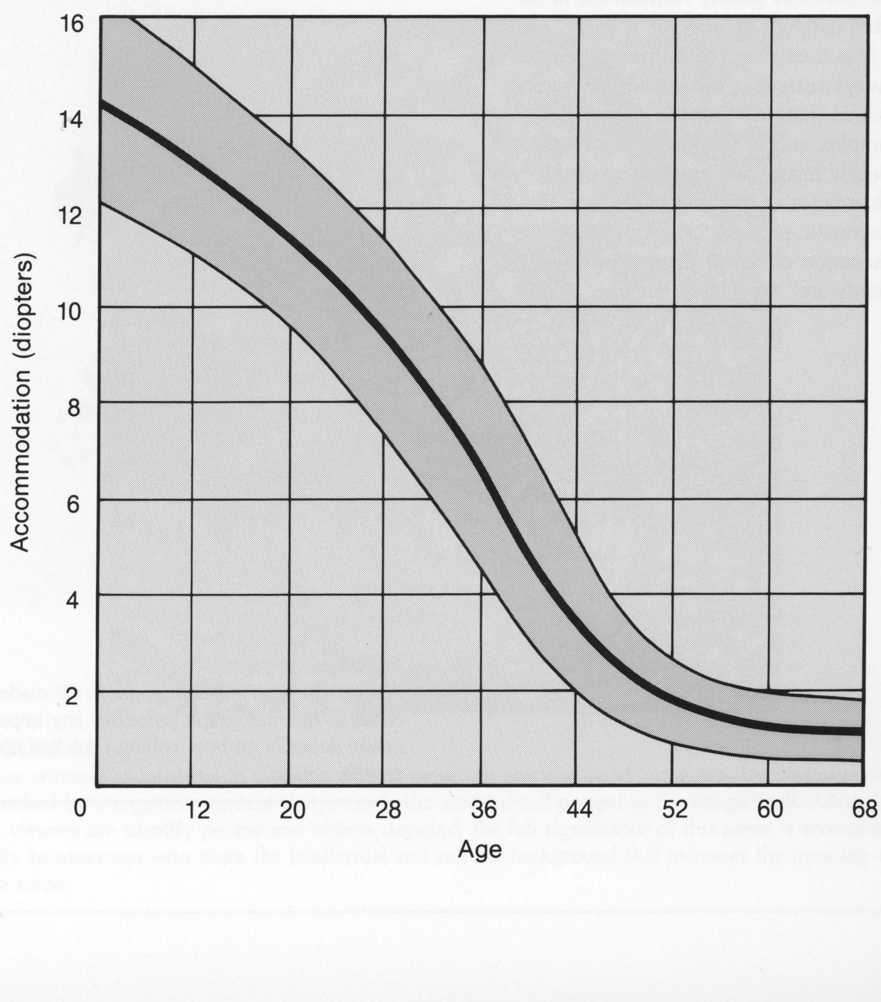


FIGURE 26
Drawing showing bending of light by cornea. The cornea is so effective at bending light that light rays that arise 14 degrees posterior to the eye are registered on the margin of the retina.

FIGURE 27
Graph showing that capacity of lens to accommodate for variable focus requirements depends on age and falls off as lens stiffens.[77]



Anterior to the lens is the iris, which can change its opening area by a factor of 16:1. The retina, on the other hand, has an adaptive response to brightness of about 10^{12}. It is thus unlikely that iris contraction would be enough to provide shading of the retina from intense illumination. More likely, its primary role may be to limit rays of light to the central and optically best part of the lens except when full aperture is needed for low levels of ambient light. It has been known since 1619[54] that the iris constricts during near vision thus reducing the amount of necessary accommodation, since this increases depth of focus during viewing of close objects. Constriction of the iris is affected by more than just ambient illumination, since it also responds to varying hormonal and autonomic control and can be seen to vary its diameter with both attention and emotional excitement.

There are several abnormalities of the anterior part of the eye that merit understanding. The first concerns hyperopes and myopes. Hyperopes (far-sighted people) have best vision at a distance, and myopes (near-sighted people) see best in close. The normal lens focuses best for objects that are 20 feet distant, but becomes more convex as the object approaches the eye. Degrees of myopia and hyperopia are measured in diopters. The normal eye of an adult can accommodate by 5 diopters to focus at 0.2 metres. The hyperope must accommodate by 1.5 diopters merely to focus on distant objects and must increase accommodation by the same 5 diopters to focus at 0.2 metres, thus requiring a total of 6.5 diopters for the same focusing range. Hyperopia (in the form of presbyopia) is a common occurrence by middle age and is undoubtedly caused by stiffening of the lens. On the other hand, when compared with those who have normal vision, myopes function as if they had an additional lens for near vision. In general, these people have a relatively long eyeball (each diopter of myopia corresponds to a theoretical elongation of 0.37 mm).[75] Only recently, it was discovered in animals that modest changes in early visual experience can result in eyes of increased axial length, and thus myopia may have both congenital and acquired causes.[78] The hereditary aspects of myopia have been the subject of some interesting historical studies of such families as the Medici.[79] Myopes tend to squint in an effort to reduce the size of their pupils. This is equivalent to attempting to look through a pinhole, thus improving the focusing of far objects. In fact, the word "myope" comes from the Greek words meaning "to shut eye."[74] Because myopic vision is superior to normal vision for near-object detail, it is speculated that medieval manuscript illumination was a task primarily performed by myopes (Figure 28).

The normal shape of the lens varies with species; not every lens is symmetric about its axis. The horse's lens is wedge shaped, providing the best retinal focus for near objects lying in the inferior visual field and for far objects located in the superior visual field.[60] Such a simultaneous arrangement would have presumed evolutionary benefits, inasmuch as the horse feeds on objects in the near field which are in best focus and occupy the lower portion of his vision, while predators need to be sighted at a distance and more likely occupy the superior portion of the visual field. Other biologic variants of the lens are evident in diving birds, which must be particularly versatile because they must see well both in the air and under the water. Cormorants, for example, have 50 diopters of accommodation.

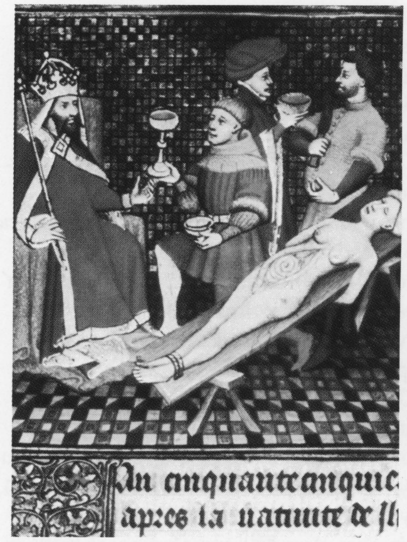


FIGURE 28
Page of medieval manuscript. Because of the fine detail that occurred in this period where glasses were unknown, it is believed that the illustrators were congenital myopes who would have had supra-normal near vision.

Another optical problem arising in the anterior part of the eye is astigmatism. In this condition, asymmetry or deformation of either the cornea or the lens (usually the former) results in the lengthening of visualized objects, most commonly in the vertical plane. The issue of uncorrected astigmatism has been raised to explain possible unintentional distortion of drawn figures by a number of prominent artists including El Greco and Holbein. The arguments and counterarguments, although fascinating, will not be discussed here.[80] Practical correction of focusing and astigmatic problems awaited the invention of eyeglasses. Although lenses in the form

of "burning glasses" were described as early as 423 B.C. by Aristophanes and later by Pliny (A.D. 77), their use as an aid for vision was not mentioned until Alhazen and Roger Bacon (Figure 29).

Although claims of inventors and reinventors of eyeglasses abound (among them Salvino degli Armato [Figure 30] and Alexander da Spina), no one person deserves full credit. From the evidence in paintings and written descriptions, however, there is little doubt that eyeglasses appeared in Italy as early as 1286.[81–82] Convex glasses were recognized at that time, but concave lenses did not appear until the beginning of the sixteenth century. Astigmatism wasn't known until 1801, when Thomas Young demonstrated it in his own eyes. Full clarification of the mechanisms of errors in accommodation and refraction, however, did not occur until the work of Donders and Helmholtz in the nineteenth century.[83–84]

The posterior orbit contains a number of structures whose properties are often not fully recognized. As previously explained, the reason the ophthalmoscope needed to be invented is that one cannot usually look into the eye and see the retina. Light is prevented from entering the eye, except through the pupil, by a dense black pigmented structure called the uvea that is composed of choroid and lined by the retina. The absence of this pigment in albinos permits light to diffuse through the cornea and makes the eyes of an albino look pink in normal light. From the standpoint of optics, the lack of pigment is quite undesirable because light that diffuses the eyeball interferes with vision.[74] In humans, this black pigment prevents not only the external entrance of light through the cornea but also the back reflection of light from the wall of the retina into the chamber that would result in a reduction in visual sharpness. Just the opposite is true in animals adapted to nocturnal life. In these animals, a comparable membrane evolved to reflect light back into the retina.[60] In the cat, for example, a greenish membrane called the tapetum reflects light. It is this light emerging back

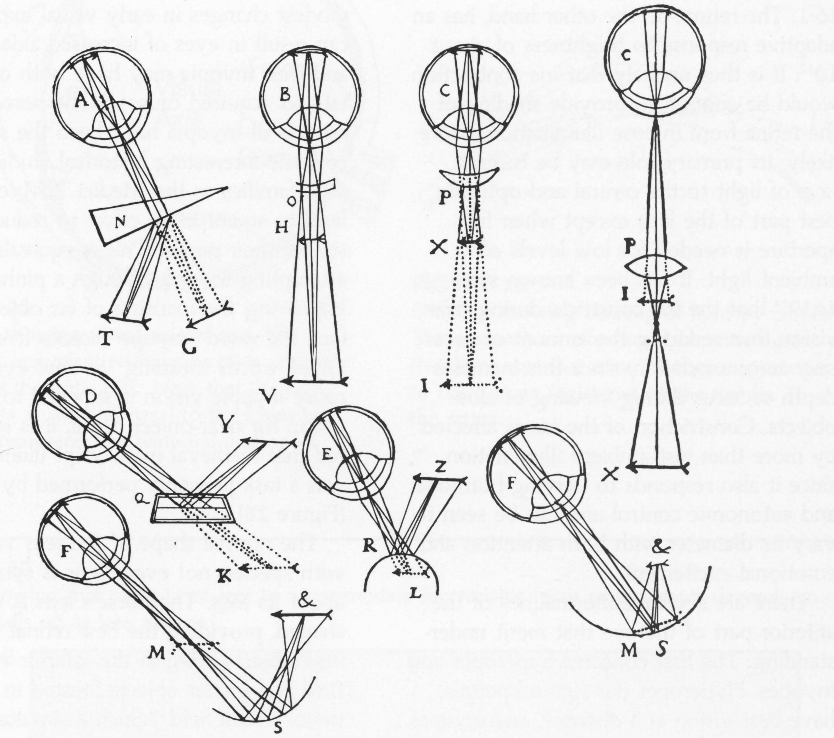


FIGURE 29
Drawings of one of the earliest rigorous mathematical treatments of physical optics, the eye, and the effect of lenses are to be found in Descartes, L'homme (Paris 1664).

FIGURE 30
Bust of Florentine inventor D'Armato credited with inventing eyeglasses. The inscription also says "May God Forgive Him His Sins."

through the pupil that gives the cat's eye a greenish cast at night. The evolutionary advantage for nocturnal animals is that receptors have a second chance to absorb incident light; they do so, however, at the expense of some visual sharpness.

The retina represents one of the most interesting biologic puzzles, since it is known to be oriented inside out, with the blood vessels and the back of the receptor neurons oriented closest to the intraocular surface. There are approximately one million optic nerve fibers. There are, however, 7 million cones and 120 million rods. Because no simple point-to-point correspondence between points on the retina and places in the brain can be invoked, it is evident that some form of neural signal coding must occur. The rods and cones are connected to bipolar cells, horizontal cells, and amacrine cells that are in turn connected to ganglion cells, and from there the connections are made to the optic nerve.[85] The cones operate primarily in daylight (photopic) conditions; the rods, primarily in a dark-adapted (scotopic) environment. The distribution of rods and cones is not uniform across the full arc of the retina[86] (Figure 31).

The optic disk, which is located at the point where the optic nerve and the blood vessels penetrate to exit from the retina, is called a "blind spot," because both rods and cones are absent over this 5-degree field. Medical students are commonly taught how to locate the blind spot quickly using either a finger or the head of a match (the red color of the match is ideally suited to the task). It is not commonly recognized, however, that the visual field in that area possesses some interesting asymmetric properties (Figures 32 and 33).

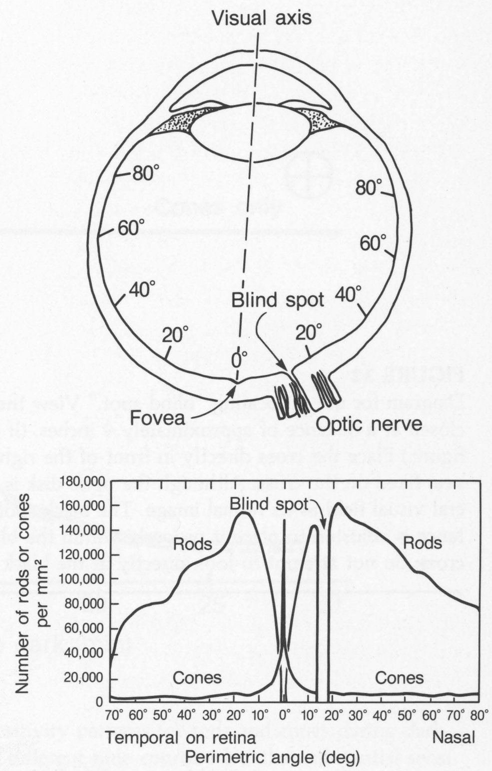


FIGURE 31
Angular distribution of rods and cones measured from fovea, which is usually axial center of eye. Note that the cones are densely clustered at the fovea providing the best acuity for photopic vision in that region. The peak density of rods occurs more laterally. The implications of the distribution of rods and cones are discussed in the text.

FIGURE 32
Diagram for use in locating "blind spot." View the figure with the right eye open and the left eye closed at a distance of approximately 9 inches. (If you view the figure with the left eye, invert the figure.) Place the cross directly in front of the right eye with the attention (and, therefore, the fovea) fixed on the cross. Although the optic disk is located nasally from the fovea, it receives the lateral visual field as its retinal image. The black spot, therefore, will totally disappear when the distance is adjusted to place it properly within the blind spot. Remember to keep your eye on this cross; do not attempt to look directly at the black spot!

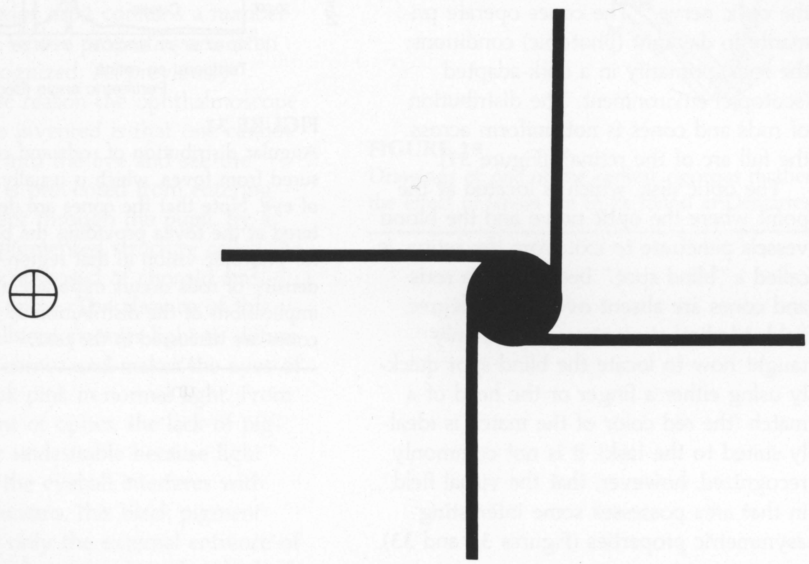


FIGURE 33
Diagram illustrating nonlinear retinal phenomenon not usually appreciated consciously. Use the technic described for Figure 32 to make the black circle disappear into the blind spot; do not look directly at the "spokes." The two vertical lines will appear to be one continuous line, but the horizontal lines will remain separated.[87]

Another important landmark in the retina is the macula, the darkly pigmented area in which the fovea is located. The fovea contains only densely packed cones in a region 1 mm in diameter.[68,74] The fovea centralis subtends less than 1 degree of arc and can be less than 100 cones in diameter. A cone is approximately 1μ in size and is equal to 2 wavelengths of blue-green light. The fine visual acuity in attention-directed vision is controlled by the fovea, and the normal search pattern of the eye usually places the fovea at the center of visual attention.[88]

In the external visual field, the fovea encompasses an area approximately the size of a dime at a distance of 15 inches. As one moves laterally, cones and rods are mixed; but at the edge of the retina, there are very few cones. In addition to their greater acuity, the cones are the mediators of color vision. Because the rods and the cones are distributed in an anistropic manner, the retina functions so that its visual acuity and its capacity to recognize color are greatest at its center and least at its sides, whereas its sensitivity to low light is greatest at its sides and least at its center.[67-68] Rods contain the pigment rhodopsin, also called visual purple.[89] The absorption of light by rhodopsin exactly matches the results from psychophysical tests of the spectral light sensitivity of the dark-adapted eye.[90] Rhodopsin is bleached by light, but it is half regenerated in approximately seven minutes. Results of sensitivity studies show that the eye is more sensitive to green and yellow light than to red and blue. Because of the different spectral sensitivities of the rods and the cones, the dark-adapted eye responds best to green light, whereas the light-adapted eye is most sensitive to yellow.[91] This phenomena is known as the Purkinje shift. The rates of dark adaptation for

cones and rods have different time constants (Figure 34). The rate of retinal dark adaptation illustrated in Figure 34 is a stable physical constant that justified the wearing of deep red, dark-adapting glasses prior to the widespread use of image intensifiers for fluoroscopy[92] and belies the impression of some older radiologists who behaved as if they believed they were adequately dark adapted in just a few moments.

The minimal energy-detection sensitivity of the eye under ideal conditions corresponds to approximately 100 light quanta striking the cornea. Taking into account the absorption and scattering that occurs prior to the light's reaching the retina (greater than 50 percent), and the 20 percent absorption efficiency of the rhodopsin in the rods, it can be estimated that perhaps as few as 15 quanta striking the retina over an area containing about 500 rods are necessary to evoke a perception of light.[74] Thus, perhaps only a single quantum of light may be sufficient to activate a rod,[93] though this single event may not be sufficient to produce a sensation of light. Cone systems are less exquisitely sensitive and require approximately 5 times as many quanta to generate a perception of light. Moreover, cones are more directionally sensitive and less responsive to photons that hit them at a glancing angle.[94] Despite these limitations, it is possible, under ideal conditions, for the dark-adapted eye to see the flame of a single candle at a distance of seventeen miles.[95–96]

From the foregoing observations, one might conclude that the brightness of a radiograph illuminator could vary considerably without affecting visual ability. If this is so (and it is), then why do we stress that view boxes be of uniform brightness? We do it because differences in view-box brightness are often misinterpreted as being caused by differences in the exposure of the radiographs placed on them. Such mismatches in view-box brightness can lead to situations in which "film" readers complain about underexposed radiographs because the illuminator used for checking the radiographs as they emerge from the processor has a different brightness than the illuminators used to read radiographs.

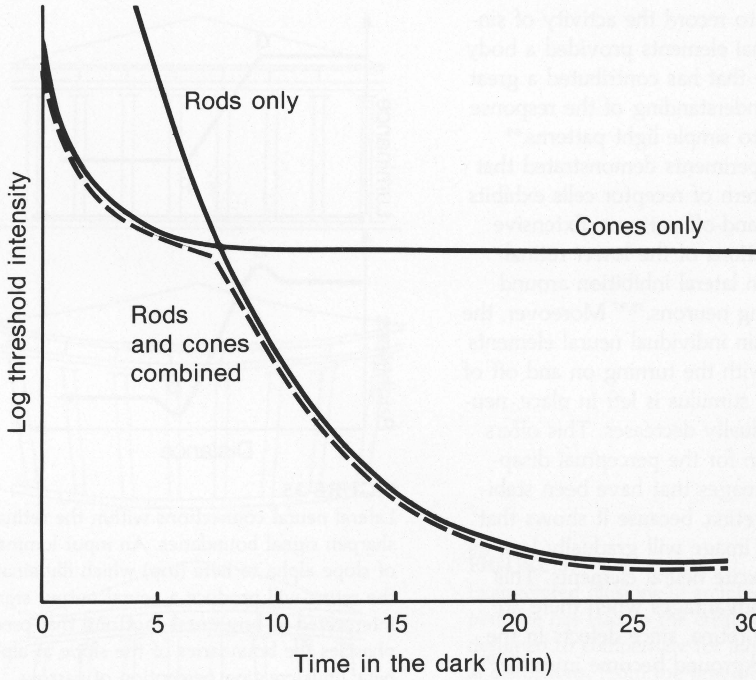


FIGURE 34
Graph demonstrating temporal dependence of sensitivity patterns for rods and cones during dark adaptation. Note that each type of receptor has a different time constant but that substantial sensitivity in a scotopic environment cannot occur for several minutes.

It is important, however, in discussing sensitivity to distinguish between measures of absolute thresholds as opposed to differential sensitivity—thresholds which describe contrast discrimination and will be more fully discussed later.

Although everyone would concede that the retina possesses a blind spot at the optic disk, the preceding description of the spatial distribution of rods and cones in the retina indicates that a second blind spot actually exists. This second blind spot occurs only in the dark-adapted eye at the fovea centralis because it is composed exclusively of cones. Dark adaptation, by definition, makes the fovea centralis inoperative, since rods are absent in that region. It may be difficult to accept this impairment until one performs a simple experiment: attempt to read a newspaper by the light of the moon—a frustratingly impossible task made further annoying by the additional realization that color is absent. It is absent because the color mediating action of the cones is shut off in scotopic vision and images in this condition are registered in tones of gray. Image intensifiers were a very important advance, since they permitted fluoroscopy under photopic conditions and alleviated the severe visual impediment of foveal blindness arising from dark adaption.

Central Neurologic Connections

The capacity to record the activity of single neuroretinal elements provided a body of knowledge that has contributed a great deal to our understanding of the response of the retina to simple light patterns.[64] Results of experiments demonstrated that the firing pattern of receptor cells exhibits particular on-and-off patterns. Extensive lateral connections of the lower retinal levels result in lateral inhibition around center-on firing neurons.[38,97] Moreover, the firing of certain individual neural elements occurs only with the turning on and off of stimuli. If the stimulus is left in place, neural firing gradually decreases. This offers an explanation for the perceptual disappearance of images that have been stabilized on the retina, because it shows that the stabilized image will gradually lose its capacity to excite neural elements. This has obvious advantages when there are defects in the retina, since defects in the stabilized background become invisible.[98] These neural signal phenomena, described in great depth by others,[38,40,41] are conceptually important because they permit a physically deterministic basis for explaining the Mach band phenomenon that is observed at a much higher cognitive level (Figure 35). This phenomenon is subtle but demonstrable in everyday diagnostic work, and the reality of its impact has been pointed out in several radiologic publications[99–107] (Figure 36).

The Mach band phenomenon permits the eye to have an increased sensitivity for boundaries and aids visual edge detection.[39,108] The success with which neurophysiologic data permitted explication of this human visual response has encouraged the search for other physical signals that would permit more deterministic models of human visual behavior. Recording and mapping the neurologic signals at the geniculate body and the visual cortex[109–110] have permitted some conclusions to be drawn concerning possible explanations for spatial frequency sensitivities.[111–114] Evoked cortical potentials from visual stimuli of very crude patterns have shed some light on cortical processing, but there are as yet no models that are sufficiently comprehensive to predict the ultimate cognitive response to anything but the simplest of patterns. Split-brain experiments performed on people who have had surgical severing of the corpus callosum demonstrate the importance of interactions between the visual cortex of each hemisphere and other portions of the brain. For example, when a stimulus was shown only to the left half of the visual field (which in binocular vision is projected almost exclusively to the right hemisphere), patients with a severed corpus callosum verbally denied the presence of the stimulus and yet were able to point to it manually.[115] This illustrates that a perception located in the visual cortex of the right hemisphere cannot be expressed as verbal knowledge unless nerve fibers permit connection to the speech centers of the brain located in the left hemisphere. This has stimulated substantial scientific speculation about the separate natures of verbal and nonverbal knowledge.[116]

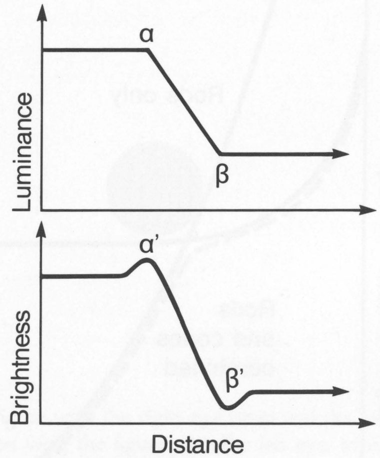


FIGURE 35
Lateral neural connections within the retina sharpen signal boundaries. An input luminance of slope alpha to beta (top) which illuminates the retina will produce a neural output signal interpreted as brightness (bottom) that preemphasizes the boundaries of the slope at alpha[1] beta[1] thus creating perception of narrow bright and dark bands at the transition of a luminance step.

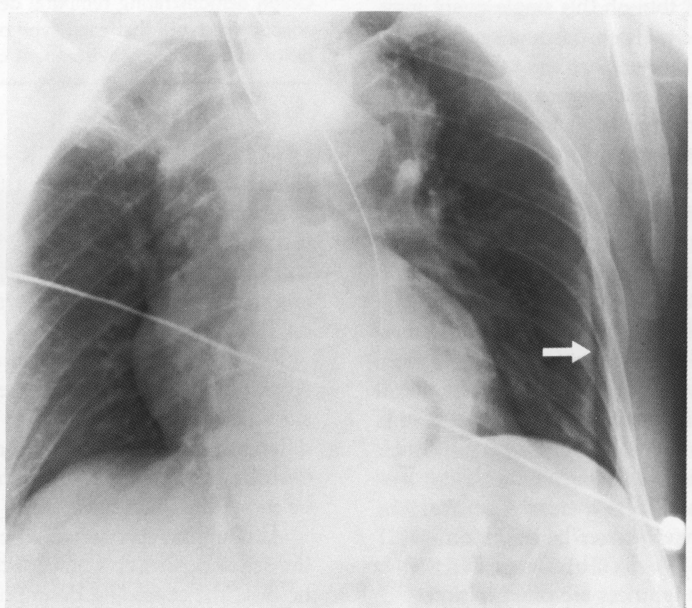


FIGURE 36
Enhancement of edge perception by Mach band phenomenon in everyday clinical radiology. The line (arrow) created by the tissue fold over the chest is more visible than would be possible on the basis of the density gradient alone. Mach band effects can often be identified by noting that the darker side of an edge contains a faint line of increased luminosity. This finding is a cognitive phenomenon: it is not warranted by the actual density gradient of the radiograph itself.

Rational Knowledge vs. Perceptual Phenomena

In medical imaging, it is the outcome, the diagnostic conclusion, that is all-important. This consideration would argue that the cognitive properties of the process should be weighed far more importantly than individual contributions of subordinate physical phenomena.[117] It would not be helpful if a biologic signal flowed smoothly and predictably into the construction of an image that possessed properties causing it to be consistently misconstrued or distorted by the inherent limitations of the human cognitive process. Clinical examples will follow, but first one might consider evidence that rational knowledge may not necessarily correct or override visual perceptual errors. Most dramatic is a consideration of optical illusions. Most people consider optical illusions (not to be confused with hallucinations, which have no base in physical reality) to be exceptional visual phenomena not present in everyday life.

The description of a visual event as an "optical illusion" often suffers a pejorative connotation, but it can be shown that optical illusions pervade everyday experience.[118–119] Take, for example, any projection image such as a posterioranterior radiograph of the chest that is reduced to a two-dimensional plane. The posterior ribs are magnified more than the anterior, but this is usually not perceived as a misrepresentation. It is occasionally necessary to modify physical reality in order to satisfy cognitive appearances by knowingly distorting objects. Nowhere is this better illustrated than by the well-known modeling of columns in the construction of a Greek temple (Figure 37).[120] A variety of innocent patterns can give rise to disturbing optical illusions (Figure 38).

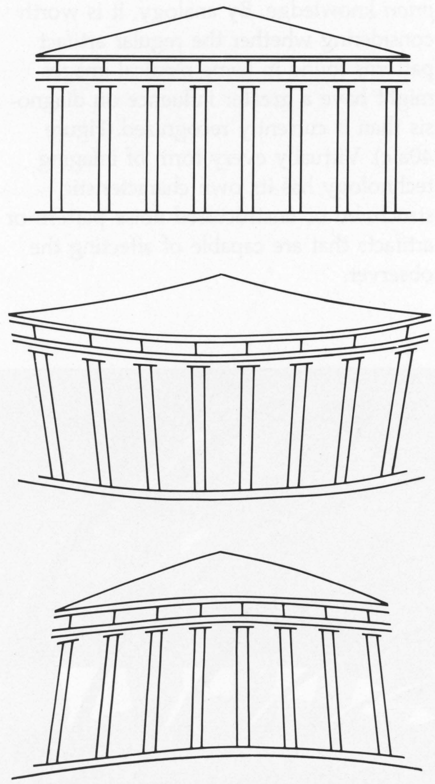


FIGURE 37
Exaggerated illusions in architecture. Long experience has lead to the creation of practices designed to compensate for inherent perceptual distortions. From the time of the ancient Greeks, building columns have been shaped to create the perceptual illusion of straightness when the actual use of a true straight line would cause a disturbing sensation.

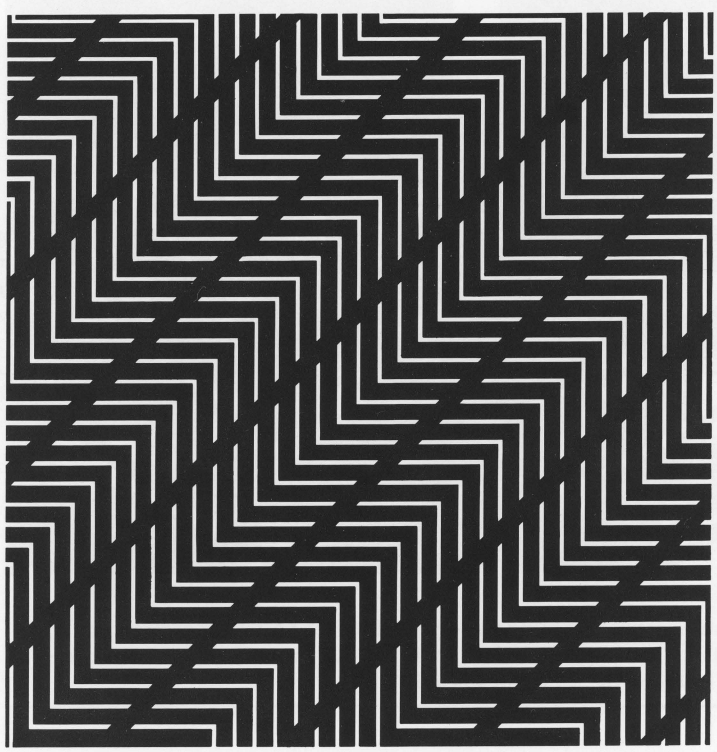
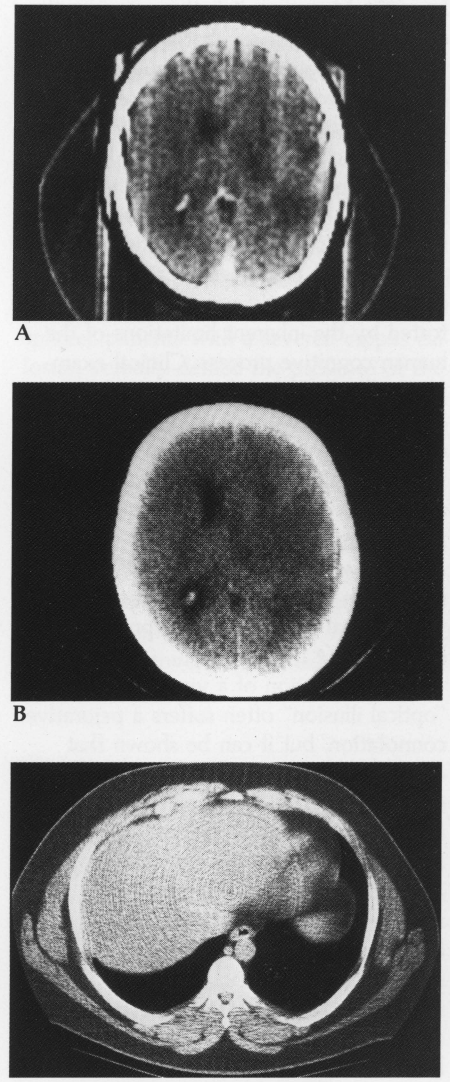


FIGURE 38
Optical illusion. Certain well-known patterns evoke measurably distorted perceptions. The diagonal lines in this illustration are, of course, actually parallel.

It is worth examining the illustration reproduced as Figure 39. Although the observer can be told that the figure is in reality a series of concentric circles (proved by tracing its path with a pencil), nevertheless, the image cannot be visualized as anything other than a spiral. The rational knowledge of the true geometry of the figure fails to aid in correcting the cognitive misperception, which cannot be transformed either by an act of will or *a priori* knowledge. By analogy, it is worth considering whether the regular artifact patterns found in some medical images might have a greater influence on diagnosis than is currently recognized (Figure 40a-c). Virtually every form of imaging technology has its own characteristic structured or unstructured noise pattern or artifacts that are capable of affecting the observer.



A

B

C

FIGURE 40
Computed tomograms made with two different types of equipment. All medical images contain artifacts (noise), and some technical solutions to the problem produce more visibly structured patterns than others. Comparison of the images shows that A has more vertically oriented streak artifacts than B and the neural tissue has a more pebbled appearance. The grain in B is finer, but it seems to have lower contrast. The subdural space is less well defined in B, although this could be altered by the use of a different mathematical convolution kernel. Substantial practical problems arose in early third-generation CT scanners because they required careful suppression of the "onion skin" artifact, as shown in C, which is unique to the geometry of these scanners.

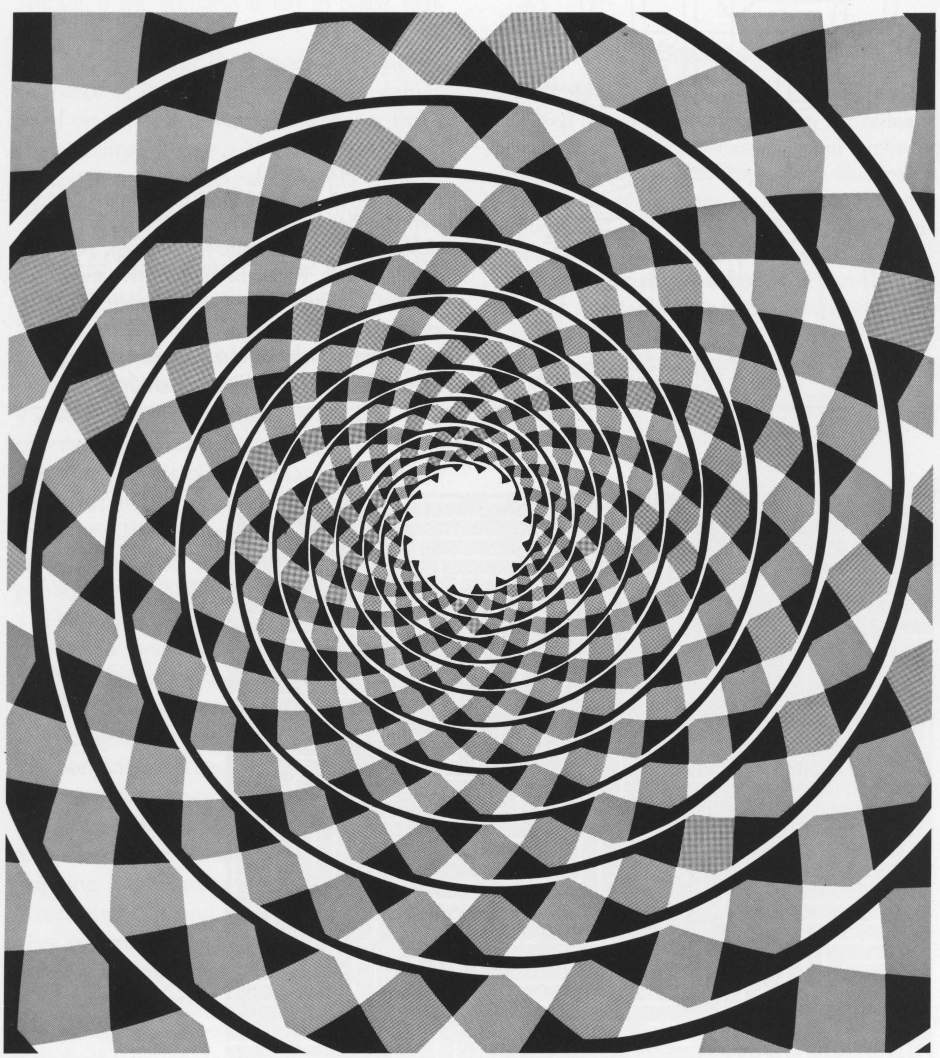


FIGURE 39
Optical illusion demonstrating that rational knowledge itself cannot adequately compensate for visual perceptual distortions. What appears to be a spiral is actually a series of concentric circles. This can be proved by following the lines with a pencil.

A number of the new electronic imaging technologies possess very strong and regular patterns of structured noise, and it may be appropriate to adopt a healthy skepticism to claims that specific forms of noise structure can be ignored and are nondetrimental to a recognition of diagnostically important information contained within the image[121–125] (Figures 41a-d and 42).

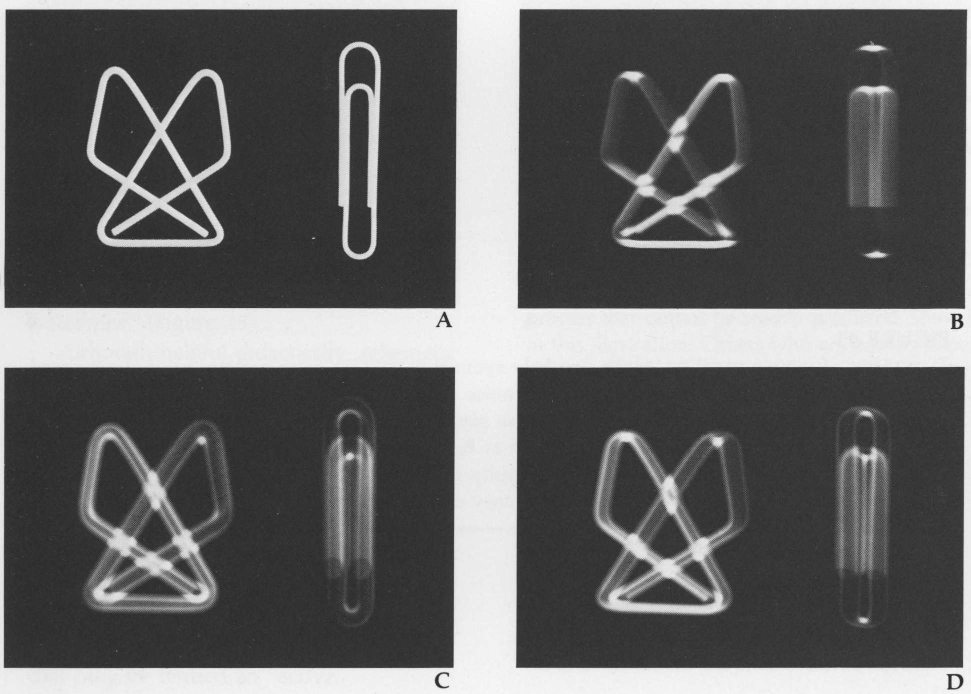


FIGURE 41
Tomograms of two paper clips. Certain types of imaging procedures produce highly structured artifact patterns. The nature of the blur pattern in conventional film tomography is characteristic of the particular tube motion chosen. A: Static. B: Circular motion. C: Linear motion. D: Hypocycloidal motion. Note in particular the differences in the crossings of the larger paper clip. Physical cut thickness capacity alone may be an insufficient justification for the choice of a tube motion. There is still too little knowledge to determine what impact adventitial blur patterns will have on the recognition of objects of particular orientation and spatial frequency.

FIGURE 42
Digital subtraction angiogram. This technic used to make the angiogram is a particularly prominent example of an imaging technic that produces a very high level of structured and unstructured noise.

Other investigators have shown that the probability of detecting abnormalities depends on both the contrast of the lesion and the complexity of the structures that surround it.[126] Therefore, measures of "conspicuity" have been put forward which attempt to account for contrast, surrounding complexity, size, and edges all at once.[127] In some instances, the medical radiographer may have to choose from alternative technologies that provide recognizably different, highly structured, artifact patterns. That choice may be influenced by physical specifications of equipment during the same time that possible perceptive interference to objects of diverse and unpredictable shape are ignored. Yet structured noise has definite effects on the detectability of lesions and the rates of film-reader error[124,126,128–132] (Figure 43).

In the absence of fundamental knowledge which could predict the response of the visual system, display choices are often inappropriately made on the basis of a pleasing image appearance.

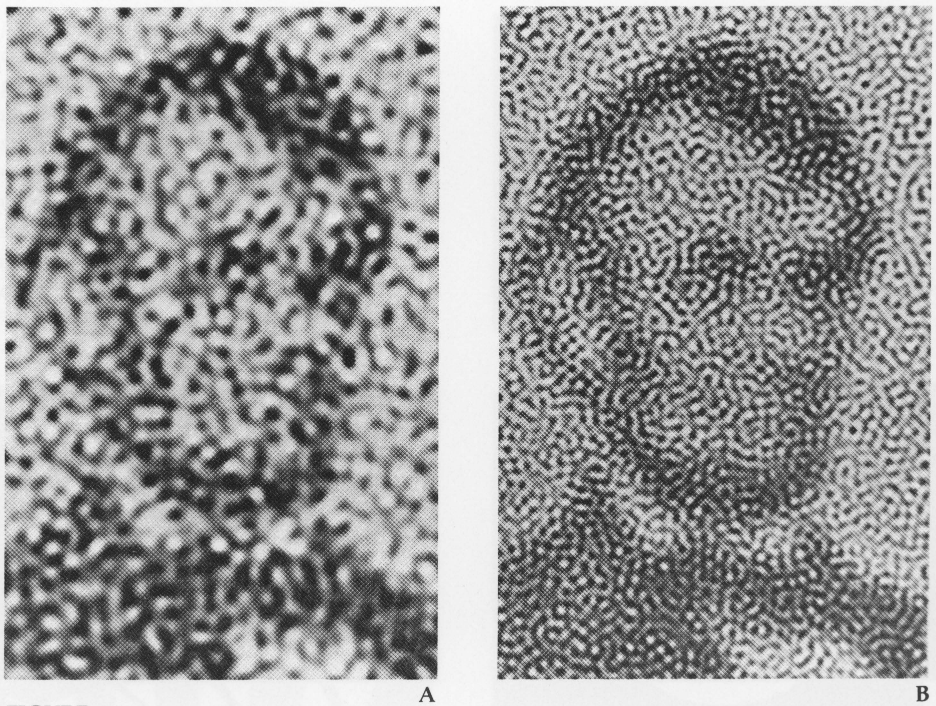


FIGURE 43
Two views of same portrait on which circularly symmetric random noise patterns are superimposed. Visual psychophysicists have explored specific noise characteristics that can inhibit the recognition of an object. In the image shown as A, the noise spectrum was immediately adjacent to the signal band of the portrait. In the image shown as B, the noise was no closer to the spectrum of the portrait than two octaves. The greater difficulty in recognition created by the pattern of noise in A is evidence that critical-band impairments may exist.[124]

Optical Illusions in Context

To an extent, the recognition of a complex visual pattern is the end product of multifactorial genetic, cultural, and educational influences. Leaving aside the genetic and early experiential influences, which undoubtedly contribute to our perception of simple geometric forms, vertical lines, and the recognition of objects important to survival and sexual functioning,[133] many visual scenes can only be interpreted with specific prior training and exposure to the tangible or intangible objects portrayed[134] (Figure 44). Inasmuch as training clearly enhances the recognition performance in complex visual tasks, it can be logically argued that a knowledge of disease processes and a probabilistic feeling for the likely location of disease helps direct the trained medical observer to search the visual field and detect objects not recognized by an untrained observer. Occasionally, however, such training can give rise to misleading and inappropriate outcomes[25] (Figure 45).

Although helpful didactically, schematic attempts to separate detection from more global cognitive steps oversimplifies a complex phenomenon. Because these processes can never be practically separated, the problem can be aptly summarized by the interesting conundrum: "A subtle abnormality in a complex field cannot be detected until it is recognized and cannot be recognized until it is detected." The visual brain undoubtedly works in a way that may be termed an "active grasp."[120,135-136] The brain is continually engaged in a feedback process, by means of which raw visual inputs are tested against reality maps that are continually updated and modified by experience.[35] This unconscious process of active testing usually improves, but occasionally degrades, visual performance. Its trial-and-error operation offers an explanation for the confusing results that occur when a familiar object is first displayed out of focus and then the focus is then gradually sharpened. Object recognition is actually impaired under these circumstances probably because the cognitive first estimate of the identity of the object intentionally displayed out of focus can be wrong and this first impression can impair later recognition even when a properly sharpened image is later presented. This psychological phenomenon might be responsible for some errors of omission that occur when a radiologist gradually changes the density display levels and windows on an electronic console.

FIGURE 44
Complex pattern. The recognition of a pattern within an unfamiliar complex field is a cognitive process that cannot be readily predicted. Some readers will immediately see the Dalmation present in this illustration. Others who are equally experienced with dogs will have more difficulty. (Photograph by R. C. James in Lindsay and Norman, 1977.)

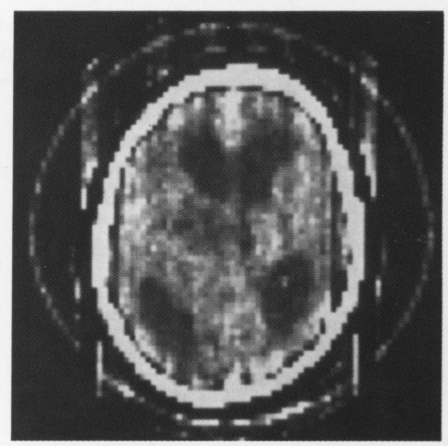


FIGURE 45
Early CT scan of the head shows how training and object familiarity can occasionally mislead. Clinicians interpreting this scan confidently identified the dense line beneath the skull as representing the subarachnoid space. In actuality, on these early scanners, the line arose from a signal overswing artifact and did not actually convey valid anatomic information.

Visual Characteristics—Individual Categories

Dark Adaptation

The advent of image intensifiers that permit diagnostic activities to occur under photopic conditions now obviates consideration of dark adaptation as a factor that might limit diagnostic capacity.[92,137] Universal knowledge of the actual time requirements of that adaptive process (in which rods and cones have different time constants), however, would have helped set guidelines for optimal performance before image intensifiers became available. Wider knowledge of these curves would have provided reasons for skeptical consideration of the performance of individual practitioners who sometimes asserted that they were adequately adapted after only a few moments in darkness.

Brightness ("Contrast") Discrimination

The extent to which the eye possesses a potential for brightness discrimination is very important from the standpoint of display equipment[138] design, but it is nonetheless commonly misunderstood.[139] The answer to the question "How many brightness levels does the eye see?" is highly dependent on context[68,140–145] and is profoundly affected by the structure and the nature of the edges present within the scene.[67-68,122,146–149] It is said by some investigators that the contrast sensitivity of the eye is 2 percent with a sharp border but 20 percent or more if the boundary is diffuse.[150–151] Take, for example, a stepped wedge. We know from previous discussion of Mach bands that the sharp boundary between one step and the next stimulates a perceptual emphasis of the edge. Moreover, saccadic motion of the eye across boundaries is necessary for maintenance of contrast perception. In the stepped wedge illustrated in Figure 46, each dark step seems to be slightly lighter near its boundary with the next darker step. This perceptual phenomenon does not accurately reflect the physical radiance actually present, since each step is in fact a completely uniform level of gray undistorted at its edges. The presence of the

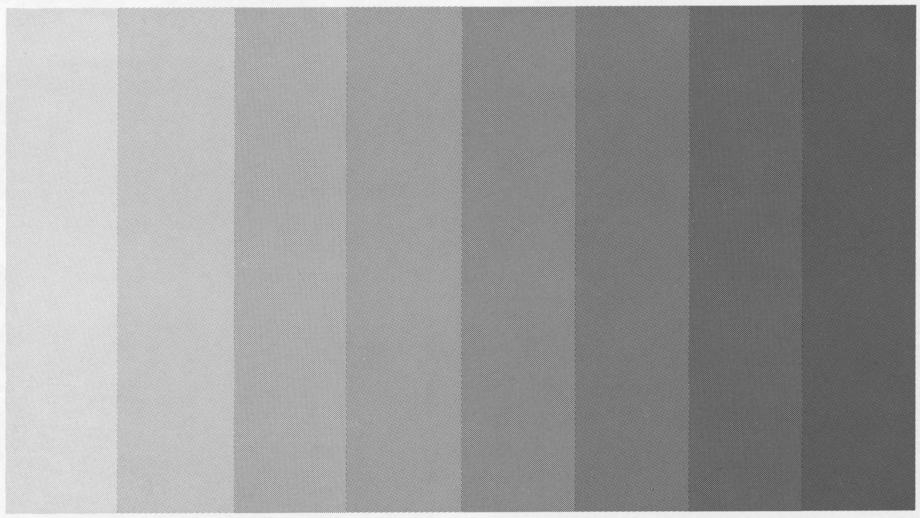


FIGURE 46
Step wedge display used as a test for brightness discrimination. The presence of Mach band phenomena seen at the boundaries of each step strongly influence visual perception. Test results using a wedge of similiar luminosity range but with boundaries obscured would yield different results.

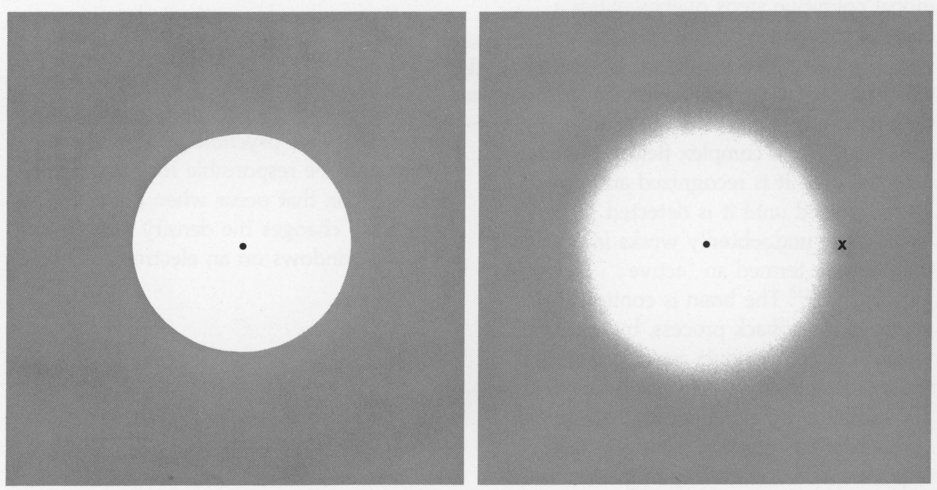


FIGURE 47
Figure illustrates the importance of image boundaries in contrast perception. Preservation of contrast perception requires some eye motion across image boundaries. The figure on the left has readily apparent contrast differences defined by a sharp circular boundary. The figure on the right possesses the same contrast but has a more gradual boundary. Normal eye motion permits that contrast to be appreciated but if the eyes are steadily fixed the perception of contrast in the image will gradually be lost.[152]

Mach bands aids in the discrimination of a given number of brightness levels; a test result that counts a certain number of steps recognized would render an entirely different result if the same intensity range were presented without sharp boundaries (Figure 47).

An accurate estimate of the limits of the brightness discriminatory ability of humans has an important impact on the design technology of medical imaging. Designers of electronic displays frequently must make decisions about costs or other trade-offs involved in presenting images with brightness scales of 16, 32, or 64 levels. Although a television display containing 64 levels probably sufficiently exceeds human discrimination requirements, it is likely that actual performance measures depend heavily on the complexity of the image and the presence or the absence of sharp boundaries within it. That the edge gradient of an object of given contrast can affect its detectability in medical images seems firmly established,[153–154] and a judicious choice of technical factors, such as kilovoltage in radiography of the chest, can definitely affect detection accuracy.[155]

Two more observations can be made concerning visual estimates of brightness. The first is an apparent contradiction to what was said previously concerning the interaction between edge boundaries and brightness. Under certain circumstances, a perception of brightness differences can occur where there is neither an edge nor an actual luminance change[156–158] (Figure 48).

The second condition that illustrates another fundamental visual limit is demonstrated by the obvious effect that surrounding densities have on one another, leading to confusions in judging absolute and relative levels of brightness. This is particularly true when equal luminance patches are separated by a distance[136] (Figure 49).

A vivid demonstration that best illustrates the interaction between contrast discrimination and patterns of varying spatial frequency shows that human vision has a peak contrast sensitivity at a frequency of approximately 3 to 6 cycles per degree of visual angle[65–68,71,159–163] (Figure 50). These

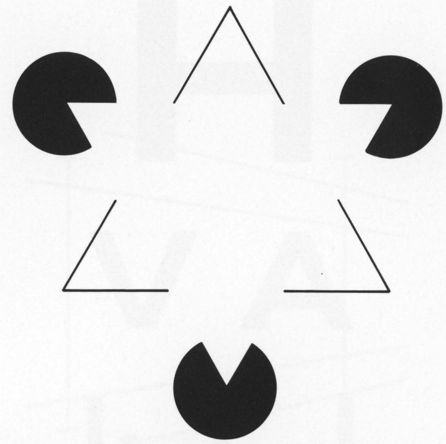


FIGURE 48
Diagram illustrating falsely higher luminosity within the central triangular region which not only has no edge boundaries but also no luminosity difference from the surrounding background. The absence of either edges or actual luminosity differences does not mean that contrast perceptions will not occur in some circumstances.

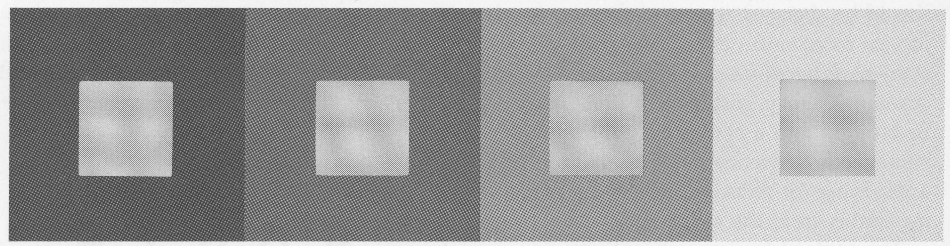


FIGURE 49
Figures demonstrating the difficulty of estimating absolute luminosity levels when surrounded by differing background densities. The center squares are actually of the same reflection density.

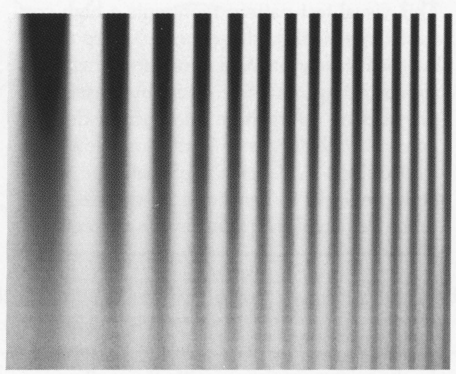


FIGURE 50
Illustration demonstrating the human observer's ability to show greater sensitivity (will be able to distinguish a much lower contrast) for contrast levels at spatial frequencies of approximately three to six line pairs per degree visual angle. A increase in contrast along the vertical axis and an increase in spatial frequency along the horizontal axis (at any one height the contrast is the same for all spatial frequencies). It should be emphasized that contrast over the whole pattern is uniformly decreasing in the vertical direction and that the observed cutoff levels at lower and higher spatial frequencies is a *perceptual* rather than *physical* phenomenon.

data confirm that the eye is most sensitive to relatively low spatial frequencies, approximately 0.5 cycles/mm or less at normal viewing distances. Moreover, it is these low spatial frequencies that seem to be most important in global object recognition, such as the identification of faces.[164] This observation seems directly pertinent to radiologic applications when the perceptibility of objects of different diameters are plotted as a function of viewing distance. The practical implications of these observations are several, since they imply that images with a resolution fidelity of more than 6 to 8 cycles/mm will be wasted for most viewing conditions unless a magnifier is used. Also, as many investigators[165–167] point out, viewing distance should be changed as part of the search pattern to optimize the detection of lesions of different sizes. Items of very low spatial frequency, such as soft tissue, may be brought into a perceptually more advantageous frequency range by the use of a minifying (or reducing) lens or by moving farther from the radiograph.

The contrast-frequency sensitivity response is not currently measured by conventional tests of visual acuity. The Snellen eye chart, for example (Figure 51), uses sharp-edged, high-contrast objects and thus only tests high spatial frequencies, since it is primarily used to uncover defects in refraction that are correctable with glasses.[168] Visual testing of the type shown in Figure 50 using gratings with variable frequency and contrast can uncover surprising impairments not detectable by Snellen tests nor correctable with glasses[169] (Figure 52). Whether the impaired contrast sensitivity for low spatial frequencies found in older people can affect diagnostic abilities in radiology is an intriguing but as yet unanswered question; but it is probably important inasmuch as object and face recognition as well as distinctions of figure from ground depend on information of low spatial frequency.[164,170–171]

FIGURE 51
Snellen chart commonly used to test vision. This visual test pattern represents a high contrast target with high frequency, sharp edges. As such it may provide information helpful for correcting refractive errors by lenses but provides no information on the individual's perceptual ability for low-frequency low-contrast objects. A deficiency of that type would be more likely to be caused by disease of the retina or neural tracts and is less correctable.

Size

Estimates of size are strongly influenced by human experience with three-dimensional space, and the eye can easily be fooled by mixing inherently planar objects with simple perspective abstractions of three-dimensional space[135] (Figure 53).

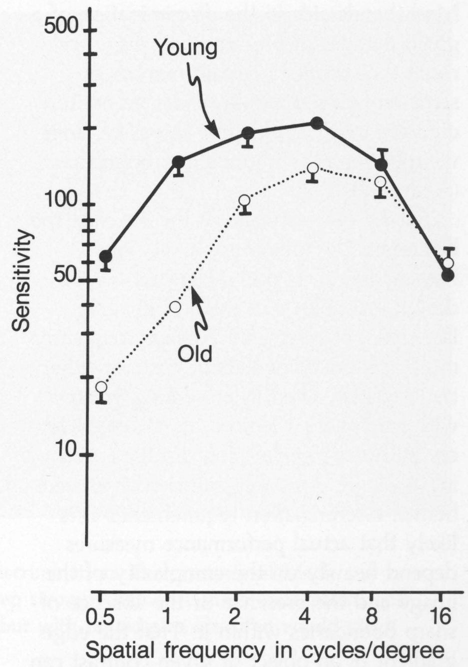


FIGURE 52
Graph illustrating differences in the contrast sensitivity function among different aged observers. When compared with young observers (18.5 ± 0.7 years), older (73.2 ± 3.8 years) individuals have impaired low spatial frequency sensitivity not detectable by current visual acuity tests (all subjects were Snellen equivalent 20/20).[169]

Errors in estimating size, however, also occur with images that are plainly flat if objects are compared with adjacent structures or arranged carefully for effect (Figure 54). Vertical distance is commonly overestimated by about 25 percent compared with an equal horizontal distance (Figure 55). The reader can easily test this: Put one black dot above another black dot on a blank piece of white paper. Then put another black dot at what you believe is an equal distance laterally. Rotate the paper 90 degrees. The difference will be obvious.[76]

Much like the effect that surrounding densities have on brightness discrimination, estimates of size are affected by adjacent objects (Figure 56), and this problem can be shown to extend to the clinical environment (Figure 57).

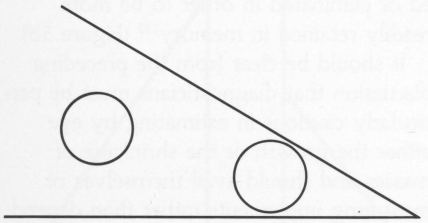


FIGURE 53
Equal size circles which appear unequal perhaps due to the perspective semblance created by the adjacent angular straight lines.

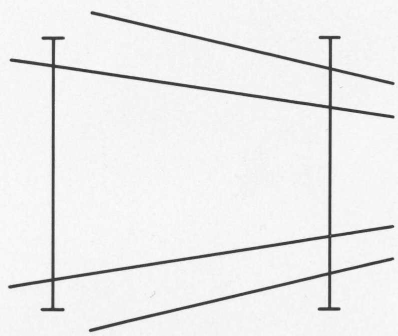


FIGURE 54
Diagram illustrating a false visual impression. Against the perspective impression created by the angled lines, the two vertical lines give a false impression of inequality.

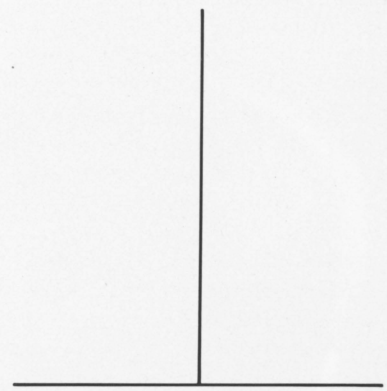


FIGURE 55
Demonstration of how vertical distance is commonly overestimated. Perpendicular lines are of equal length.

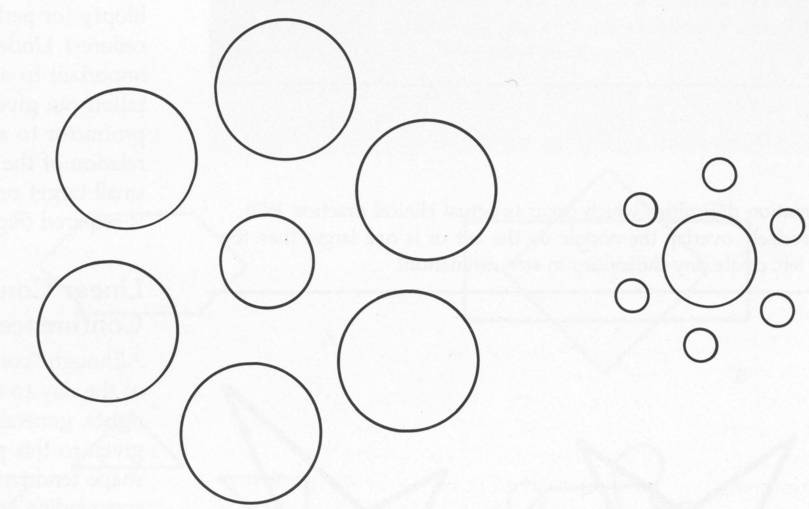


FIGURE 56
Diagrams showing how difficult it can be to estimate object size when surrounding objects cause confusion. The two inner circles have identical diameters.

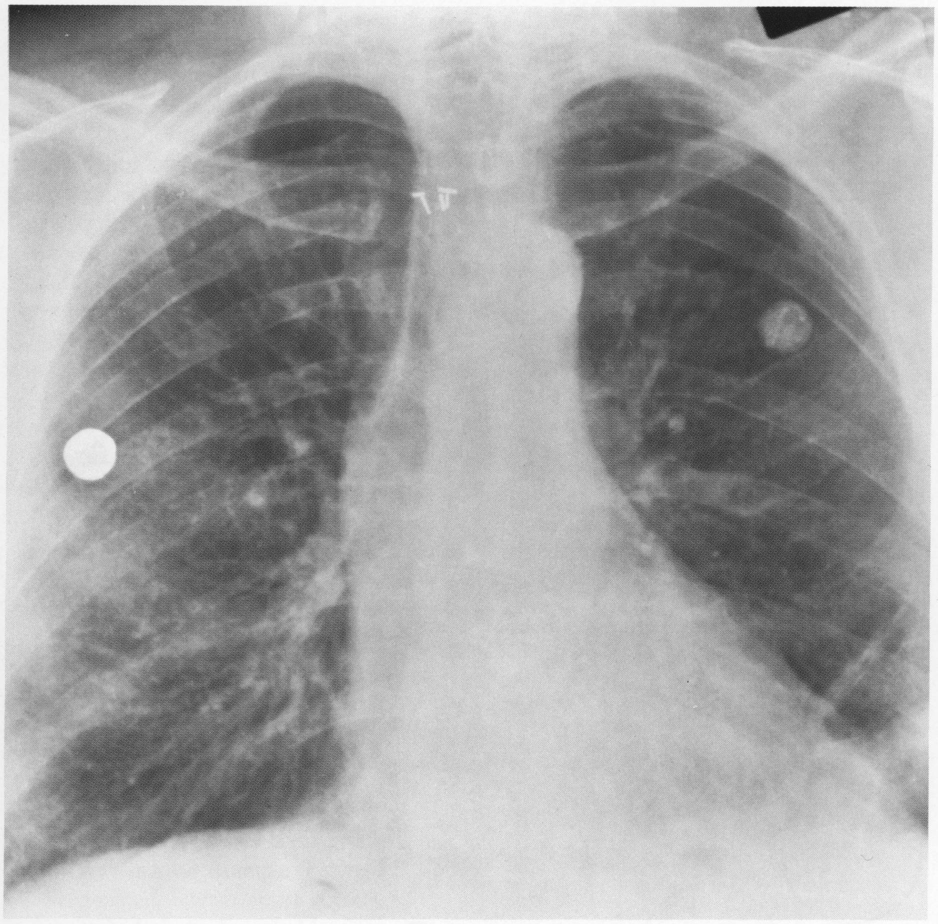


FIGURE 57
Radiograph demonstrating size estimation difficulties which occur in actual clinical practice. Will the coin overlying the right lung precisely overlap the nodule on the left or is one larger than the other? Does the missing rib on the left create any difficulties in size estimation?

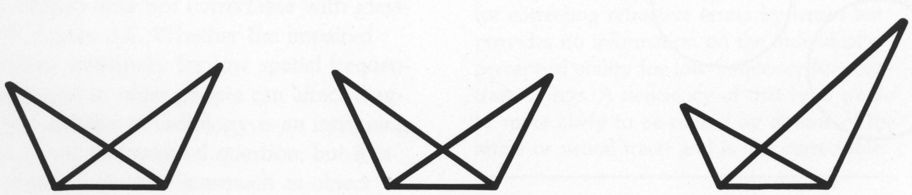


FIGURE 58
Three simple diagrams demonstrating that memory estimates of size and local relationships are easily shown to be faulty. When the drawing A is shown to observers who are asked to memorize and later redraw the figure, the resulting drawings from memory are usually created as shown in B and C. In B, minor assymmetries are suppressed; whereas in C, they are exaggerated. Memory seems to require simplification of subtle relationships in order to efficiently retain them in memory.

Another factor that complicates estimation of size is revealed when memory is employed, since mental images are constructs and not copies. The necessary conditions for estimation of size of an object and its commitment to memory very commonly require a simplification process in which subtle issues are either exaggerated or eliminated in order to be more readily retained in memory[135] (Figure 58).

It should be clear from the preceding discussion that diagnosticians must be particularly cautious in estimating by eye either the growth or the shrinkage of masses and should avail themselves of measuring implements rather than depend on the vagaries of judgment and memory.

Angle

Although in the clinical setting it is rarely necessary to estimate precisely the angle between the intersection of two lines, circumstances can occur that affect the visual capacity to perform this task accurately (Figure 59). The clinical condition in which this could be of importance is in directed biopsy (or perhaps stereotactic needle procedures). Under these circumstances, it is important to accept what help instrumentation can give or to use even a simple protractor to accurately define the angular relation of the needle to the body if a small target or precise directional accuracy is required (Figure 60).

Linear Continuity and the Confluence of Shadows

Although "confluence of shadows" is part of the day-to-day vocabulary of all radiologists, generally little consideration is given to this problem. Objects of complex shape tend to be more easily hidden by surrounding structures that possess similar features (Figure 61).

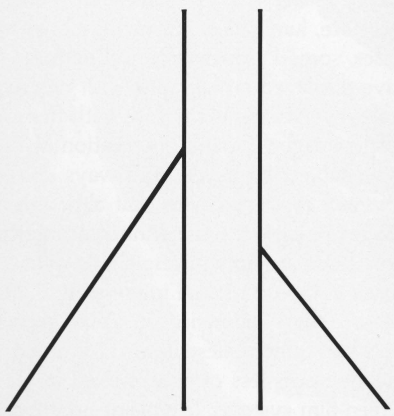


FIGURE 59
Diagram illustrating the false impression of angle. The intersection of the two non-vertical lines actually occurs at a point not expected from appearances. Use a straight edge.

FIGURE 60
CT image displaying an aid for determining precise angles. The clinical need for accurate estimation of angles may occur in needle biopsy procedures. Many types of CT equipment provide readily accessible aids for determining precise angle and length dimensions which when combined with a protractor can be used to clinical advantage.

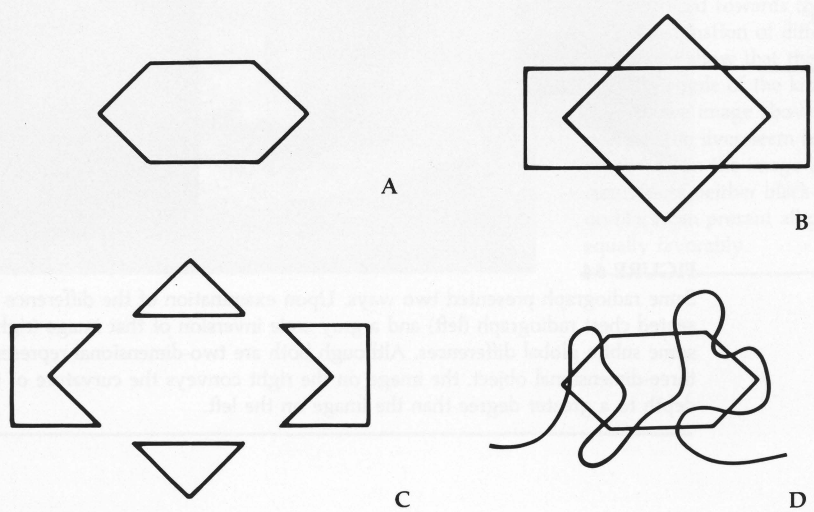


FIGURE 61
Series of diagrams demonstrating a pitfall in the recognition of a familiar shape (A). Surrounding structural patterns that have properties similar to the object itself can impede the search for familiar objects, as shown by the figure buried in panels B and C. The same object is more readily perceived in panel D since the overlying patterns possess properties that are markedly different.

The visual extraction of form from multiple intersecting lines, however, sometimes seems to follow a need to view objects as simple geometric structures and thus reduces the perceived object to its simplest shape[135–136] (Figure 62). Linear continuity is particularly difficult to assess when the figure is interrupted (Figure 63).

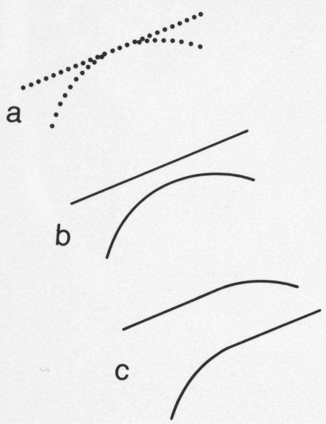


FIGURE 62
Series of illustrations demonstrating that the perceptual separation of a complex pattern often proceeds to segment it into parts of familiar simple geometric objects. Figure A will nearly always be separated into the individual parts shown in Figure B, but in fact the solution found in Figure C is just as reasonable, though less simple and familiar, and therefore, less often chosen.

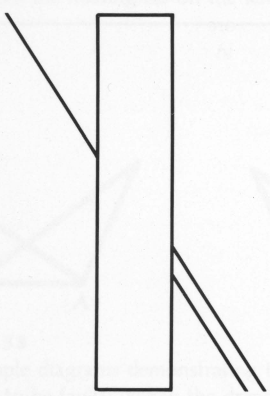


FIGURE 63
Well-known Poggendorf illusion illustrating that continuity of straight lines can be difficult to assess. Use a straight edge to determine which line is the actual continuation of the interrupted line.

Black-on-White Vs. White-on-Black

A particularly perplexing problem derives from the alternative options of registering medical images as either white structures on a black background or black structures on a white background. The perceptual differences associated with white-on-black versus black-on-white displays are not adequately understood nor is there sufficient knowledge to strictly endorse only one of these formats. Experiments with ultrasound images of small wire targets seem to suggest that type target is more accurately detected on photographic prints when presented in the "white-echo" format.[172] Those results however, might be strictly applicable only for reflective, not transilluminated images, and for small single targets rather than textures. Most radiologists are familiar with images on film in which the densest body structures are displayed as the greatest transparency and, therefore, luminance. For publication purposes, some European medical journals have displayed radiographs with this tone scale reversed, as is the case with fluoroscopic images. Careful observation of the same subject displayed both ways should convince most observers that although the images possess the same inherent information, there are nonetheless subtle differences in the perceptual impression (Figure 64a-b). These differences in visual impression defy precise description. Although this option is less often exercised in screen-film systems, it remains an important unresolved issue because electronic imaging devices can arbitrarily provide either alternative (Figure 65a-b).[173–175]

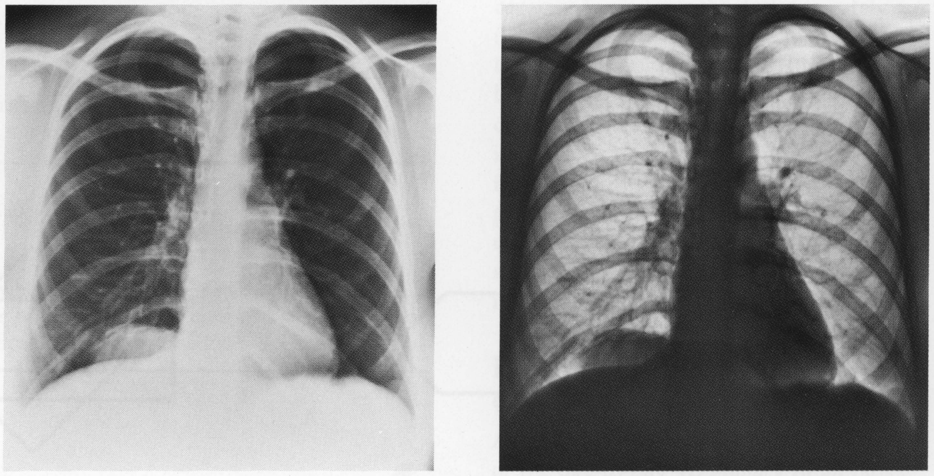
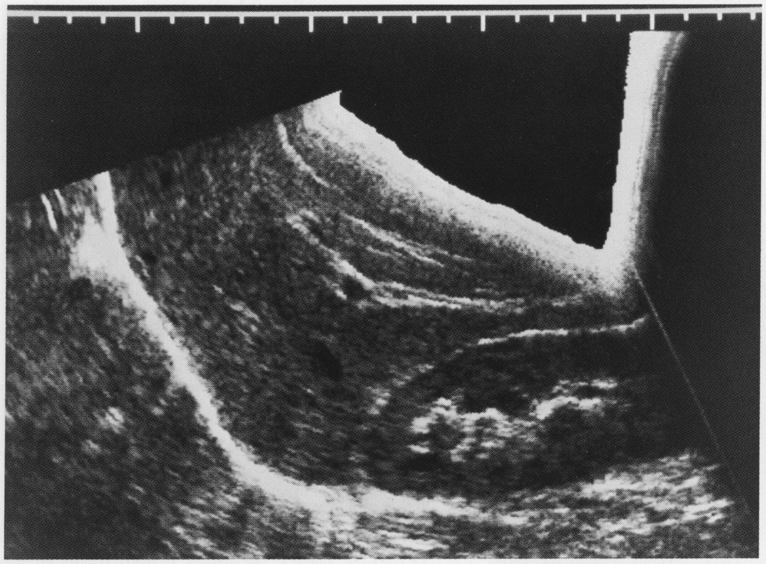


FIGURE 64
Same radiograph presented two ways. Upon examination of the difference between a normally-presented chest radiograph (left) and a gray scale inversion of that image (right), one can perceive some subtle global differences. Although both are two-dimensional representations of the same three-dimensional object, the image on the right conveys the curvature of the ribs and a sense of depth to a greater degree than the image on the left.



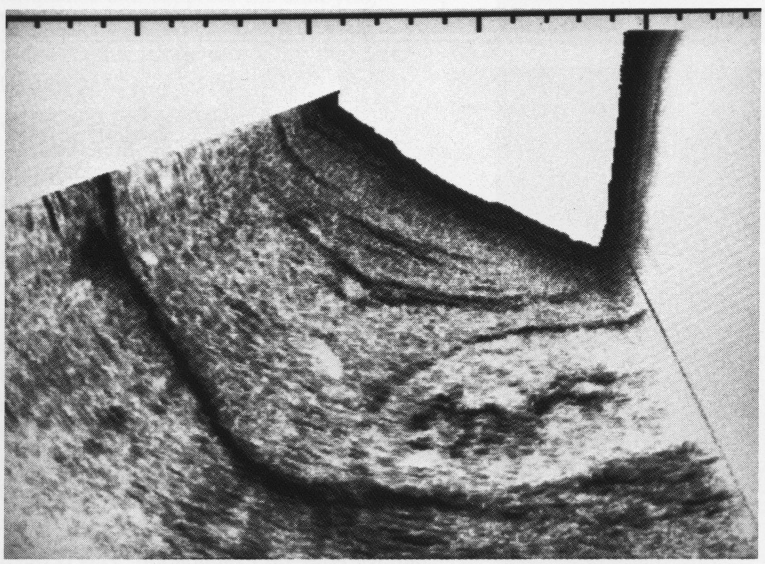


FIGURE 65
Sagittal ultrasound images of the liver and right kidney. The same image is presented in white-on-black (above) and black-on-white (below) formats. Although most viewers will be prejudiced towards their customary format, close examination of different portions of each image will show that the renal boundaries at the upper pole of the kidney seem better defined in the image above but the textural aspects of the liver seem to be more favorably presented on the image below. In most circumstances neither black-on-white or white-on-black can present all portions of the image equally favorably.

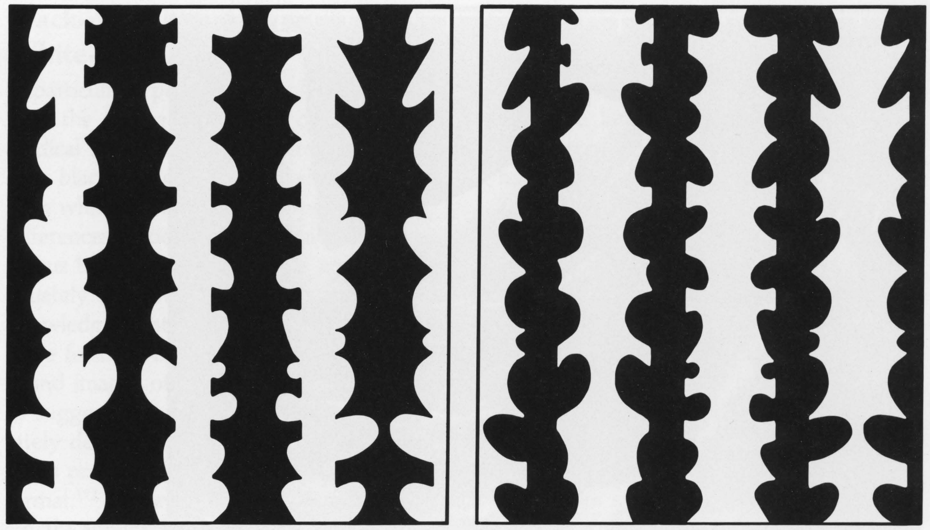


FIGURE 66
Example of the classical figure-ground problem. The left and right panels are equivalent but inverted. If one gazes at either panel long enough the figure can invert back and forth but true simultaneity of both perceptions cannot be achieved.

Perceptual differences noted in examining these figures cannot be attributable to major differences in the overall level of light, since the figures were chosen to have roughly the same net intensity level. Instead, the differences are probably attributable to a difficulty in perception identified as the "figure-ground" problem (Figure 66). The effect that training has on the choice and preference for one particular display format cannot be ignored and is likely to have some impact on the speed with which object recognition occurs. It is relatively easy to find individual clinical examples in which one of the two alternatives seems to have an advantage. Experimental attempts have been made to fuse both displays in a composite image by either rapidly flashing the normal and inverted image on a display monitor (to take advantage of visual time integration) or attempting to view the two formats simultaneously as separate sides of a stereoscopic viewer. Unfortunately, these efforts lead to an ambivalent rather than a usefully comprehensible image. As yet, no optimal solution to this dilemma has been found.

Veiling Glare

Because of the limited range of luminance possible from print images, it may not be important whether a black-on-white or a white-on-black mode is chosen. When either of these formats is presented as a film transparency, however, an important influential issue must be considered. This arises from the considerably greater amount of light to which the eye is exposed when a view box is used. If major segments of the image and the area surrounding it are transparent, potential light-flooding of the eye by intra-ocular scattering can occur that will decrease the sensitivity of the eye for detecting subtle changes in contrast in the denser portion of the image. After all, glare is the problem for which the broad-brimmed hats of cowboys and baseball players are designed.[176–180] Moreover, the effect of this veiling glare in degrading contrast detection is often understated because many experiments described in the literature were performed under idealized conditions in which veiling glare was minimized. The effect is particularly prominent in scotopic conditions. Common experience convincingly demonstrates this when the headlights of an oncoming car at night markedly reduces visibility of lower-lit lateral objects. Although recurring mention of this phenomenon can be found in the radiologic literature,[181–185] its impact on radiographic viewing is still usually ignored.

It is relatively easy to control the problem by carefully limiting the light of the view box to the margins of the radiograph being examined by shutting off the light of adjacent panels. Some automatic equipment is now available that makes this task easier, and even simple strategies such as using one's own cupped hands as blinders can be useful.[186]

These solutions should be more widely acknowledged and promoted. Most multiformat cameras presently leave transparent gaps between images, but newer models that opaque the gaps are becoming available. This is particularly important for 100 mm "spot films," which can be conveniently and effectively mounted in black cardboard masks. Otherwise large bright gaps between panels will degrade observer contrast performance.

The flood of light through large transparent areas of a radiograph may be at the heart of the empiric practice of tilting the film for edge-on examination. This is often necessary in searching for the tip of a catheter in the heart. The heart is so transparent that low-contrast objects within it are often invisible. Tilting the radiograph and looking at it at a glancing angle while squinting makes the light travel through a longer distance and thus increases the density in that portion of the film. The darker background then makes low-contrast objects such as catheters more visible. An alternative explanation is that the tilt modifies the spatial frequencies thus sharpening the edge of the catheter to improve detection.

Another problem that is often unnoticed is the perceptual effects of the television raster lines that appear on most multiformat film images. The television raster produces alternating strips of black and white over the surface of the film. When displayed on the monitor itself, the strips are often unnoticed because of the dynamic aspects of the electronic interlace, but they are easily visible when imaged in static form on film.[187] If one attempts to set the television camera for deep black, the visual effect on the film often differs from the technical goal, since the eye averages the illumination from each black line with the next adjacent transparent gap degrading the blacks into gray on the film image. Methods of raster suppression are being implemented by many manufacturers of multiformat cameras. These methods will undoubtedly improve variations in luminance and suppress the annoying horizontal structural interference in the photographic image caused by the raster (Figure 67a-b).

Visual Search

As mentioned earlier, small involuntary saccadic motions of the eye (at a rate of approximately 5 per second) are necessary to preserve edge discrimination, but larger voluntary searching motions of the eye are important during examination of a larger field of view. Numerous contributions to the radiologic literature have been made to investigate and identify the role that this visual search plays in the detection and recognition of radiologically important objects.[188–189] Training has definite effects on the manner in which the search pattern is conducted.[190] The data, however, are not clear as to how important prolonged foveal fixations are in the ultimate recognition of abnormal findings. Some efforts have been made to determine whether enforced or directed search might improve the performance of trained observers, but results so far have not shown improved detectability[191] and are often contradictory.[192–194] Sufficient variation occurs in the search patterns of trained people who have equal rates of diagnostic success that it is not clear whether regimentation of search could be helpful.

FIGURE 67
Magnified details of the corners of multiformat images with and without raster line suppression. Two undesirable results arise when the raster is not suppressed. First, there is a strongly visible horizontal structure imposed on the details of the image. The second aspect cannot be effectively illustrated on a printed page because of its lower luminosity range but when the unsuppressed raster appears on film viewed on a view box, the translucent gaps between lines transmit illumination that lowers the perceived opacity of the scanned lines and can make camera contrast settings difficult to adjust properly.

There is no question, however, that training affects the particular search pattern used and that without this training substantial portions of an image are neither searched nor recognized[195–199] (Figure 68a-b). Moreover, when one considers the effect of viewing time on detection accuracy, it appears that most true-positive decisions are clustered in the early viewing period, whereas prolonged viewing seems to increase the number of false-positives.[201]

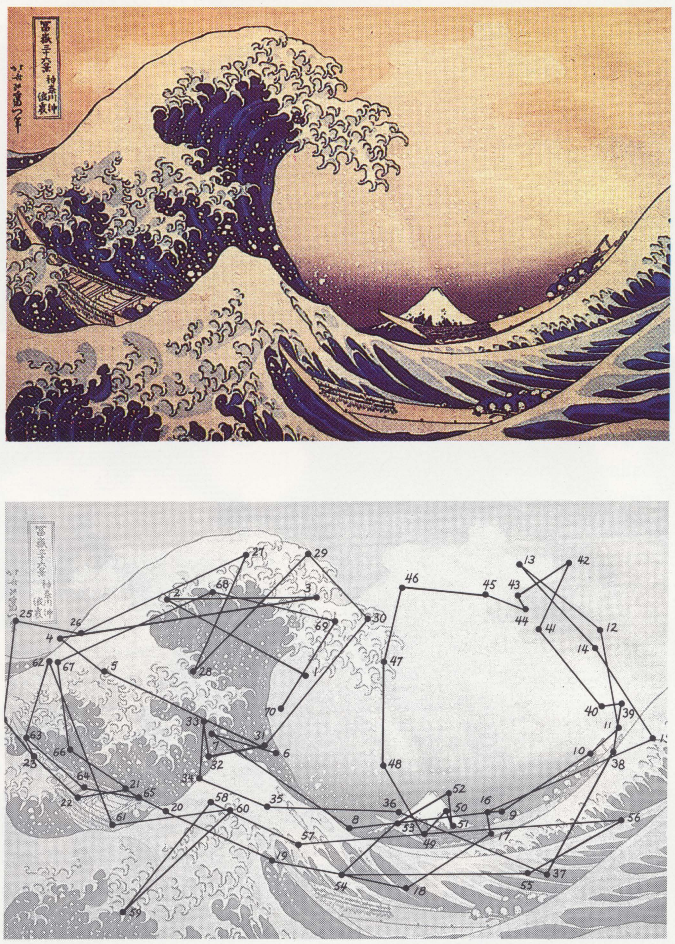


FIGURE 68
Famous Japanese print which was subjected to visual search pattern analysis by tracking the foveal motions of subjects viewing the print.[200] The foveal search progressions shown in the lower figure obviously follow the dominant curves and the dramatic form of the image. There is, however, an interesting omission when one looks again at the original. The Japanese ideographic characters in the upper left are not searched at all. Although one cannot assume that these characters were not 'seen,' since writing must be progressively scanned in order to be read, this indicates that the subject was a Westerner unable to read the characters. Had the characters been in English, they most likely would have evoked sequential foveal attention. Cultural and experiental familiarity, therefore, contribute to the direction of visual search and attention.

Color Discrimination

Most medical instruments code signal intensities in black and white on the final image. Electronic devices, however, make color coding possible although its use has been restricted mostly to multiparameter overlays, such as radiotherapy fields superimposed on CT scans, or to simple intensity patterns that vary in intensity such as cardiac nuclear images. Although color displays have had some objectively testable success in nuclear medicine,[27] pragmatic experience with color coding of complex images such as CT scans has not been considered diagnostically advantageous. The justification for attempting to use color coding of the computed tomographic image is, however, based on sound scientific reasons since it can be shown that the number of individually discriminable colors is greater than 10^6 (or 1,000,000). This available display range is better matched to the large dynamic range of CT data and is considerably greater than the number of encodable gray levels in black-and-white images, which are estimated at less than 10^3 (or 1000).[202] Although some investigators[203] dispute the claim of 10^6 of "just noticeable differences" in the color scale as being exaggerated, it can still be argued that even if the magnitude of the color scale were somewhat lower, the necessity for varying the display level and the window might be reduced. Areas of isointensity would be more readily apparent to the observer when coded in color.[204]

A possible explanation for what seems to be a general failure of this approach may be the result of the richness of local point-to-point detail and complexity of the CT image (Figure 69a-g). Inherent in any choice of color spectrum for encoding signal amplitude levels is the necessity for assigning different hues for amplitude steps that may be adjacent. The eye readily accepts variations in gray-scale intensity between any two adjacent steps. In a color scheme, however, two pixels that may vary slightly in amplitude might be coded as green-red or blue-yellow, depending on the color spectrum assignment. In a complex pattern, sharp color boundaries may thus be seen at minimal intensity steps

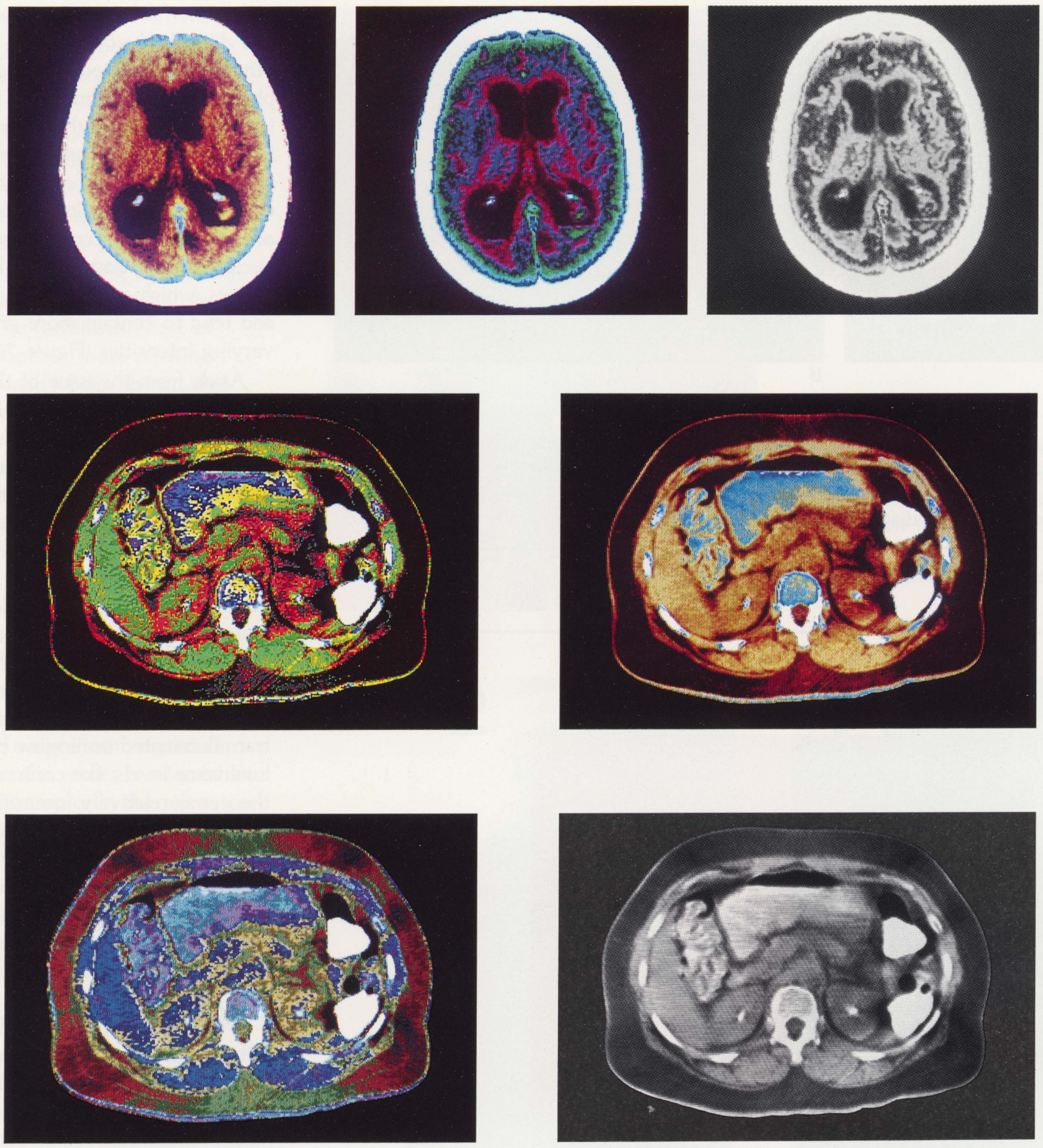


FIGURE 69

Black-and-white and several different color displays of the same head and body CT images. Although the color displays may be visually more exciting and interesting to the naive observer, most diagnosticians favor the black-and-white presentation. While the color image readily displays important organ boundaries, the complexity of the color display creates an image difficult to comprehend. The fact that color hue transitions produce very strong boundaries where only slight intensity changes have occurred also complicates interpretation of these images.

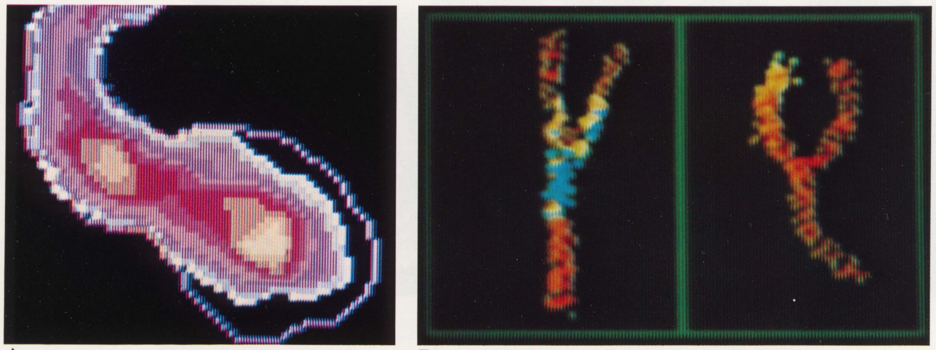


FIGURE 70
Color-encoded cardiac nuclear and doppler vascular studies. Color encoding allows a better evaluation of specific intensity changes where it is used to encode the different intensity levels of these studies. The images are sufficiently simple to be comprehensible. The use of color in this type of image, therefore, appears to have diagnostic utility and may be appropriate.

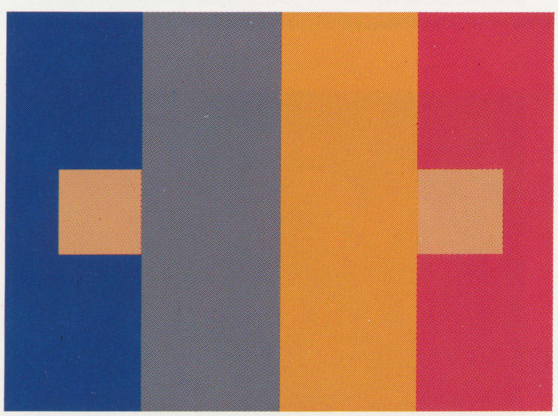


FIGURE 71
Simple illustration of a common color perception error. Two color squares that have the same hue, saturation and luminosity show how the cognitive capacity to identify colors of the same hue and saturation can be faulty. Observers will invariably identify the one on the right as being darker and more brownish.

and create false contours that are complex and difficult to comprehend. If, on the other hand, the medical image is less complex and contains smoothly varying point-to-point intensities, the color boundaries formed are less disturbing and could be advantageous in discerning the magnitude of change of signal intensity. This may account for the success of color displays in nuclear cardiac and doppler blood-flow images, which are inherently less complex and tend to contain more gradually varying intensities (Figure 70a-b).

Aside from the issue of the confusion caused by the complexity of a very detailed color image, it is also important to recognize that many other problems of color perception exist. Judgment of color identity can be shown to be faulty in a variety of circumstances[205–207] (Figure 71). This may not be notable in simple scenes, but it is clearly demonstrable when the image is complex and adjacent hues vary.

Another issue concerning color that has clinical importance is the finding that when black-and-white transparencies are transilluminated on a view box at standard luminance levels, the contrast sensitivity of the eye is relatively insensitive to the illuminant color.[208–210] This observation is reassuring, since it appears to indicate that contrast sensitivity is unaffected by a preference for either the warm (reddish) or the cold (bluish) fluorescent lights used in view boxes.

Problems in Matrix Images

When signals are acquired as a spatially discrete coarse matrix, the display of the data may create unexpected visual effects. This problem has been addressed in nuclear medicine, computed tomography, and more recently digital subtraction angiography. The rectangular edge boundaries generated in the display by the picture matrix may be scientifically faithful to the data and yet be strongly disturbing to the clinical observer[211] (Figures 72a-c and 73a-b). It has been found that finer matrix structures that require some data smoothing produce more acceptable images. This has been applied to some extent in nuclear medicine[212–214] in which the physical resolution for many types of equipment would be

adequately represented by a 64 by 64 display matrix, yet interpolated 128 by 128 matrices seem preferable to most observers.

Schemes for interpolating data and mathematical smoothing algorithms have attained the level of fine art in computed tomographic images. Some designs for CT equipment incorporate a variety of smoothing and interpolating algorithms which are primarily used to suppress artifacts but have the fortuitous effect of producing a smoother, more pleasing image. It has recently been shown that proper choices of mathematical smoothing algorithms operating on the already reconstructed CT image can provide improved detection of subtle targets that would otherwise have required greater radiation doses to achieve equal detection performance.[215]

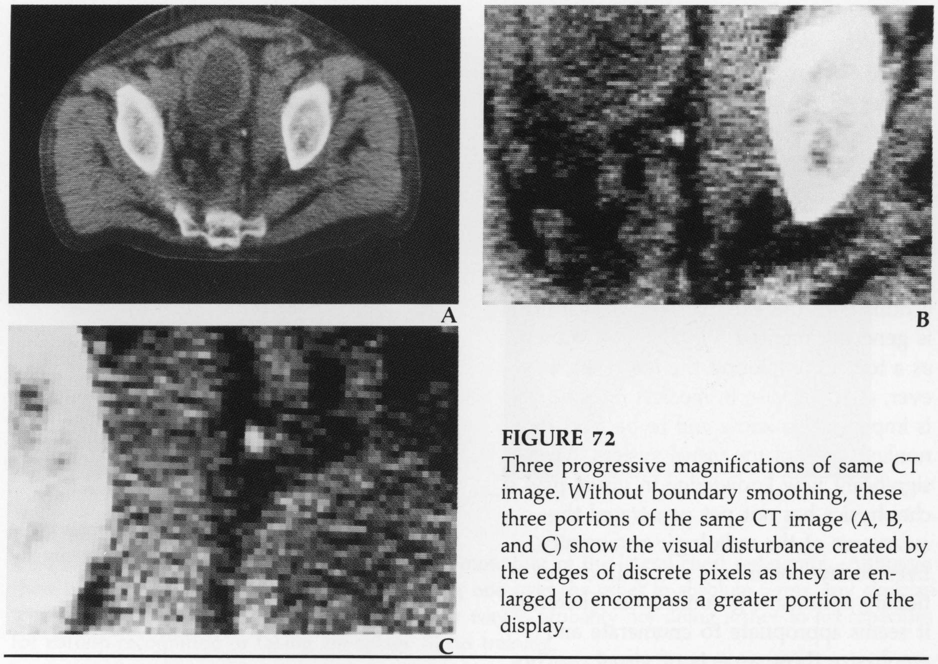


FIGURE 72
Three progressive magnifications of same CT image. Without boundary smoothing, these three portions of the same CT image (A, B, and C) show the visual disturbance created by the edges of discrete pixels as they are enlarged to encompass a greater portion of the display.

Miscellaneous Visual Problems

Many other perceptual problems can be identified, but since most of them are unlikely to have a significant impact on clinical diagnosis, the reader is referred to the selected bibliography in the reference section. Some visual problems that are likely to have a significant impact on clinical diagnosis and therefore deserve consideration include stereoscopic vision, which by using displays generated by random dots can be employed as a powerful probe of the cognitive process.[216] Visual sensitivity to flicker and the capacity of the eye to track moving objects are also interesting, but those subjects are too narrow to pursue in this paper. Suffice it to say that the flicker-fusion frequency that establishes the rate of image repetition necessary to convey a sense of smooth motion continuity increases with increasing intensity and is in the range of approximately 30 frames per second, a parameter that is generally met by most electronic imaging systems.

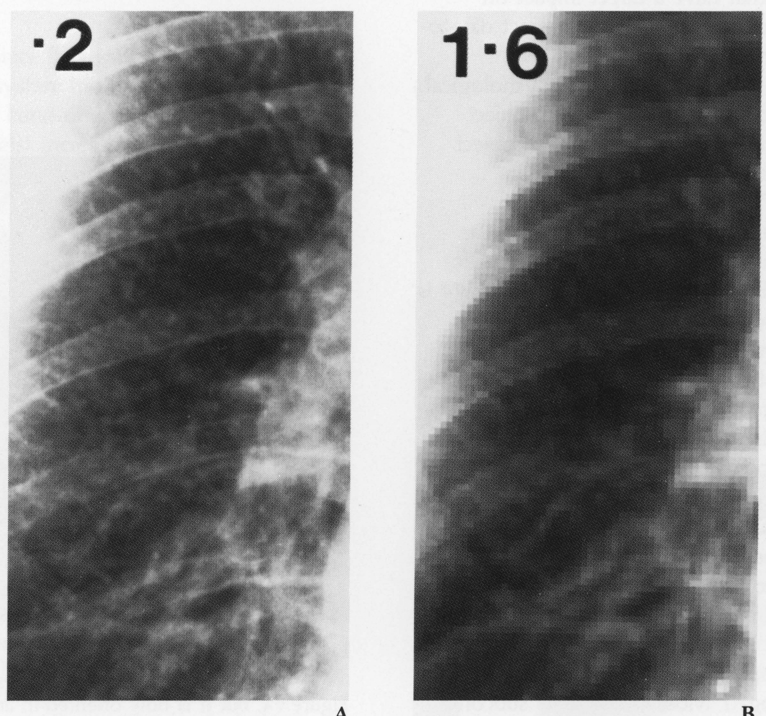


FIGURE 73
Two electronic displays of the same lung radiograph. Each contains multiple small pulmonary nodules which are shown at six levels of spatial resolution varying from 0.2 mm pixel size (2.5 lp/mm) to 1.6 mm pixels (0.3 lp/mm). For this disease entity, using receiver operating characteristic curve analysis, detection was markedly inferior for the 1.6 mm pixel size matrix.[211]

Practical Implications for Clinical Practice

It is estimated that as much as 80 percent of all the knowledge achieved by humans is acquired through vision. Most would not doubt that it is our most reliable and least easily deceived sense organ, particularly when compared with either touch or smell. This trust is deeply imbued in our language and is expressed by such statements as "Seeing is believing" and "I saw it with my own two eyes." In most interactions with the external world, such trust is generally merited. When vision is used as a tool for exploring the unknown, however, as is the case in medical imaging, it is important to know and to be alert for nonlinearities of the visual system. Much significant new knowledge in visual psychophysics has not yet penetrated the awareness of the radiologic community. Even today, commonly recognized cautionary aphorisms go unheeded. Therefore, it seems appropriate to enumerate and emphasize those aspects of visual psychophysics that have a direct impact on current clinical practice and impact day-to-day work.

(1) It is well known from psychological studies of complex images that object recognition is impaired when an object is presented in an unfamiliar orientation.[217–218] Consider Figure 74, for example. Occasionally, such unfamiliar presentations have even more dramatic effects (Figure 75). Even when Figure 74 is turned to a more conventional, but uncommon, orientation (Figure 76a), it would still be rejected by most practicing radiologists as being undesirable for attempting to obtain an accurate diagnosis. It may be useful to remember, however, that at least one university training program taught a diagnostic approach which recommended viewing radiographs from the direction of the x-ray tube. By this precept, posteroanterior radiographs were hung in reverse from anteroposterior radiographs. This practice should be discouraged. Most radiologists subconsciously realize that they are placed at a disadvantage when the orientation of an image differs from expected norms and mental templates achieved through long experience.[219–220] It is noteworthy, how-

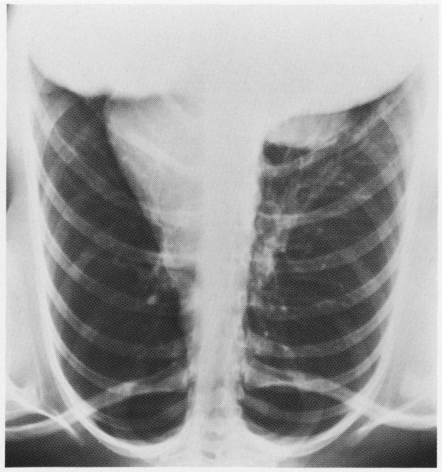


FIGURE 74
A chest radiograph offered for diagnosis but presented in this unusual way would generally be rejected by most clinicians.

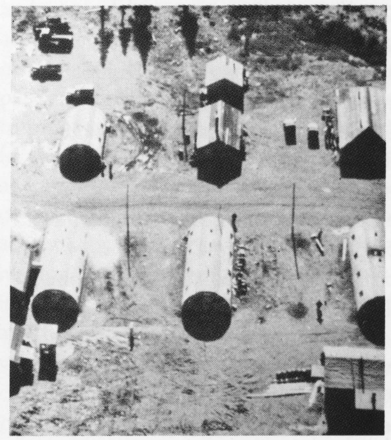


FIGURE 75
Pictures of some three-dimensional objects show dramatic changes when viewed inverted. Try looking at this picture upside-down.[117]

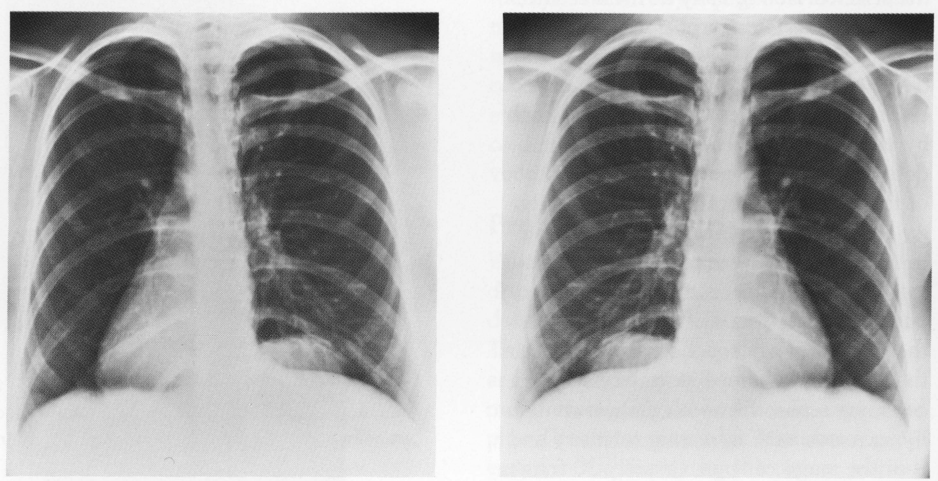
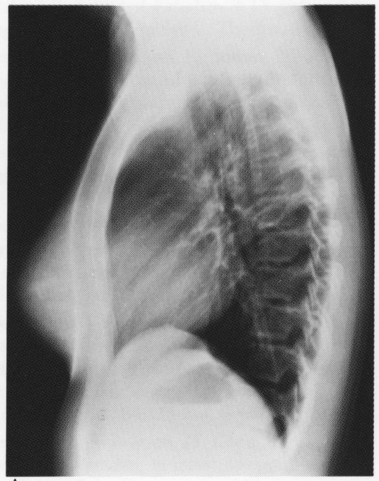


FIGURE 76
Two orientations of same chest radiograph. Left panel shows same chest radiograph as in Figure 74, but it is now oriented in an upright way. It would still make most clinicians uncomfortable because most individuals would consider it mounted backwards. In the image on the right, the chest radiograph would be considered appropriately mounted and the abnormalities are easier to comprehend.

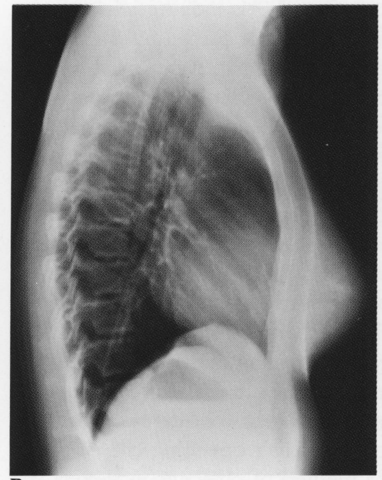
ever, that many radiologists do not feel so strongly about the orientation of all radiographs. Particularly interesting is the seeming nonchalance in mounting lateral chest radiographs (Figure 77a-b). From the theoretic standpoint, it probably matters little whether a lateral radiograph faces left or right so long as the viewer employs that same orientation consistently. When a person orients radiographs inconsistently, it could raise questions as to the effectiveness of that person's opinion.

(2) One of the most important cautions needing discipline is a lack of concern for the well-known impairment of contrast sensitivity when the eye is flooded with extraneous surrounding light. Although this point cannot be adequately illustrated in print because the luminance range of reflected images is more than an order of magnitude less than that of transparencies (Figure 78), the issue is very definitely present in viewing radiographs on an illuminator.[181,221-222] A small dark object completely surrounded by transparent film permits flooding of the eye and the retina with illumination that unequivocally impairs diagnostic recognition of subtle contrast variations within the denser portion of the radiograph.[178,183,185] In fact, the increased visibility seen when using a "hot" light is often attributable to the reduction of surrounding glare rather than to increased intensity. No amount of mental compensation or verbal excuses can correct this incapacity. The problem is particularly acute with small images such as those in nuclear medicine, ultrasound, and 100 mm spot films. Recent favorable attention by manufacturers to the mounting of 100 mm films has resulted in the ready availability of convenient opaque masks with cutouts for individual spot films to prevent lateral flooding of the eye from the adjacent light of the view box.

(3) Awareness of the vagaries of the human capacity to assess and memorize size accurately should lead practitioners to be particularly cautious in assessing size or growth of masses without the aid of a measuring device. Although this is particularly true for items such as lung nodules, it also holds true for much larger items such as cardiothoracic ratios.



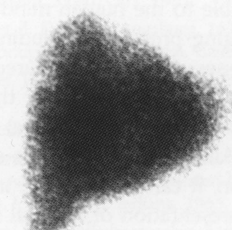
A



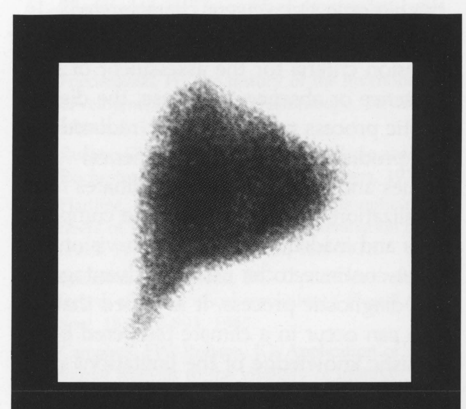
B

FIGURE 77
Two alternatives (left facing or right facing) for mounting of the lateral chest radiograph. Although there is no rigorous scientific reason for favoring one over the other in absolute terms, any clinician who nonchalantly views lateral chest films either way is probably not doing justice to his capacities for pattern recognition or taking advantage of his training.

(4) Since it is well established that the visual system has a peak sensitivity to a narrow band of spatial frequencies,[65-66] the radiologist increases his opportunity to detect lung nodules of diverse size by varying the viewing distance (or using a reducing lens) during the examination of a radiograph rather than viewing it always at the same fixed distance.[18,131,167,223]



A



B

FIGURE 78
Two versions of same nuclear medicine image. Electronic images conveyed to film transparencies are often formatted so that substantial portions of the film are translucent (upper image). Flooding of the eye with view-box light surrounding the image (which cannot be properly demonstrated in this printed example) renders the eye ineffective for detecting subtle density changes within the dense portions of the image. One need only check this by careful blocking of the surrounding light or masking closely around the important portion of the film (lower image). When this is performed, it is much easier to see subtle densities.

Conclusion

Diagnostic imaging is moving into a new era in which the role played by the visual capacities of the human being must be characterized and its limits either compensated for or knowledgeably accepted. Timely consideration of these issues is necessitated by the rapid growth and proliferation of imaging alternatives both by electronic displays of new biologic signals and by modifications that provide alternative approaches within an imaging discipline. The recognition that what is important in imaging is the diagnostic outcome rather than subjective preference emphasizes the need for attention to such technics as receiver operating characteristics as a method of objective evaluation[37,214,224–230] It behooves the medical community to be more informed and better aware of its human visual cognitive limitations. Appropriate compensation can then be made when solutions are possible and knowledgeable acceptance applied where there are none. Serious consideration of optical illusions should convince the reader that objective reality is never fully accessible to the human mind and that all imaging processes, including medical, possess inherent structured or unstructured artifacts that impair the ability to access "objective" (scientific) truth in the signal. Although it represents an oversimplification, it can be said that, in a sense, the presentation of medical information as an image might be considered an indication of failure, since science tends to present information as a visual map only when it cannot be further simplified to the rigor of discrete and irrefutable numbers. If the biologic signal were characterized sufficiently to make possible an invariant decision criteria for the assessment of the presence or absence of disease, the diagnostic process might likely be reduced to the production of abstract numerical values and spatial vector coordinates for localization. Until such time, the complexities and inadequacies of human vision must continue to be used to advantage in the diagnostic process. It is hoped that this can occur in a climate tempered by a realistic knowledge of the limitations of the visual system.

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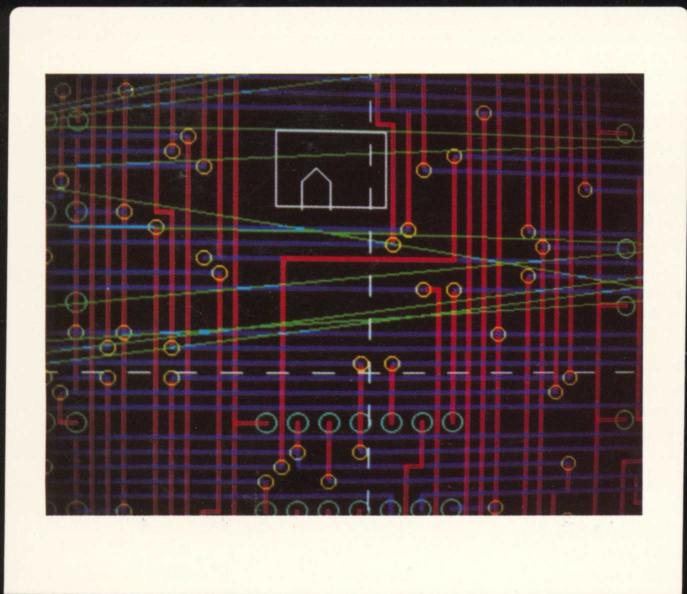

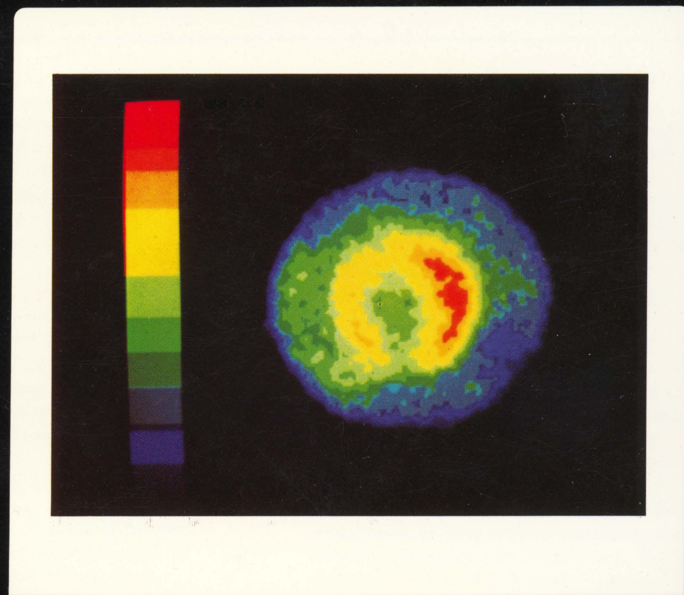

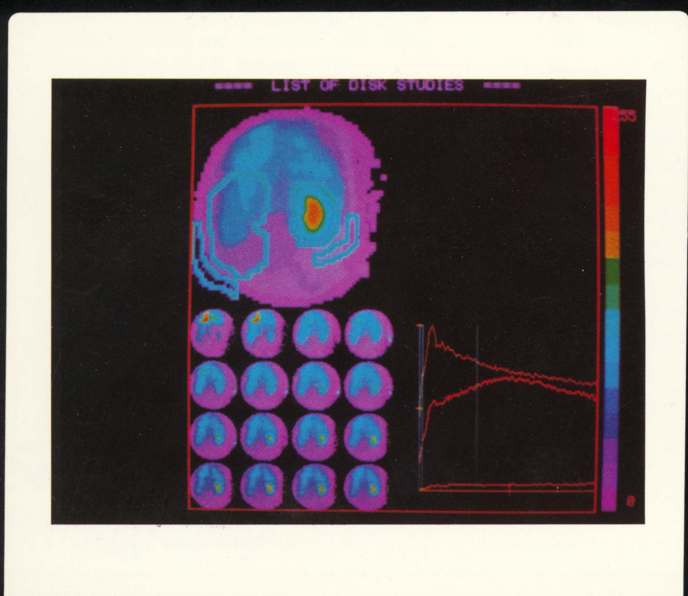

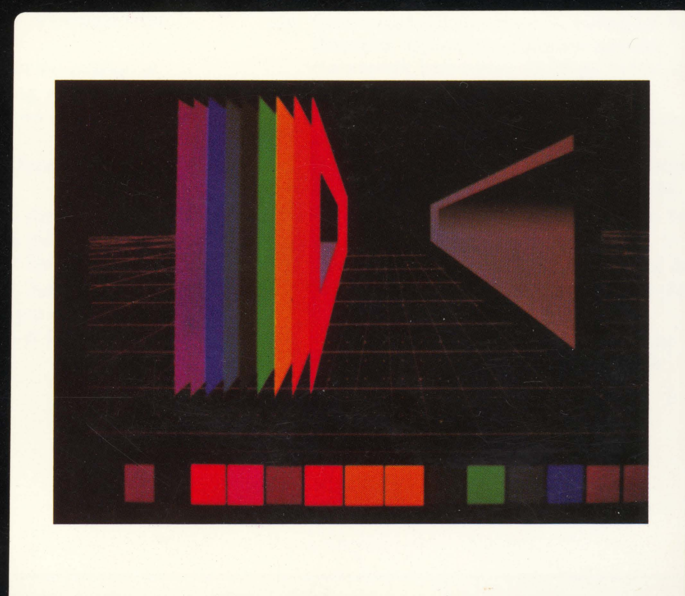

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